Using BFOLDS to characterize fire regimes: a case study from a boreal forest landscape

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Using BFOLDS to characterize fire regimes: a case study from a boreal forest landscape

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Abstract

Forest fires are the result of complex interactions of weather and vegetation and are highly probabilistic. Characterizing forest fire regimes, the synoptic properties of spatio-temporal variability of individual fires, is important for many forest and fire management purposes. BFOLDS 1.0 (Boreal Forest Landscape Dynamics Simulator) simulates forest fires and forest succession for large areas over long periods. Resulting fire regime simulations are emergent properties of many stochastic and spatially explicit model processes as well as user assumptions and input data. Here we demonstrate the use of BFOLDS in characterizing a forest fire regime, using a large boreal ecoregion as an example and readily available forest cover and spatial weather data as primary input. The simulation period was 200 years and simulations were replicated 30 times to capture the stochastic variability in spatial and temporal patterns of forest fires. In addition, we present several examples of quantitative indicators that characterize different aspects of a fire regime. These indicators include annual burn fraction (overall, by age class, and by forest cover type), fire return interval, fire size distribution, and burn probability (overall, by age class, and by forest cover type) and their spatial, temporal, and stochastic variability.

Résumé

Les feux de forêt, qui résultent d'interactions complexes entre les conditions météorologiques et la végétation, sont très probabilistes. La définition des caractéristiques des régimes des feux de forêt, soit l'établissement des propriétés synoptiques de la variabilité spatiale et temporelle de chaque feu, est importante à de nombreuses fins liées à la gestion des feux et des forêts. Le logiciel BFOLDS 1.0 simule les feux de forêt et la succession forestière pour de grandes étendues et sur de longues périodes. Les simulations des régimes des feux qui en résultent réunissent les nouvelles propriétés d'un grand nombre de processus des modèles stochastiques et spatialement explicites, les hypothèses de l'utilisateur et des données d'entrée. Dans cet ouvrage, nous montrons comment le simulateur BFOLDS peut être utilisé pour caractériser un régime de feux de forêt, en prenant une grande écorégion boréale comme exemple et en utilisant des données météorologiques spatiales et sur le couvert forestier facilement disponibles en tant qu'intrant principal. La période de simulation était de 200 ans, et les simulations ont été répétées 30 fois afin d'enregistrer la variabilité stochastique des tendances spatiales et temporelles des feux de forêt. De plus, nous y présentons plusieurs exemples d'indicateurs quantitatifs qui caractérisent divers aspects d'un régime des feux. Ces indicateurs comprennent la proportion de la superficie brûlée annuellement (dans l'ensemble, par classe d'âge et par type de couvert forestier), l'intervalle de récurrence des feux, l'étendue des feux et la probabilité de feu (dans l'ensemble, par classe d'âge et par type de couvert forestier), de même que la variabilité spatiale, temporelle et stochastique des feux.

Acknowledgements

Contents

Introduction

Forest fire regimes and particularly boreal forest fire regimes are dynamic processes and are stochastic, that is, they involve chance or probability (Cui and Perera 2008, Lertzman et al. 1998). Understanding their characteristics is becoming very important in forest and fire management planning in the context of sustainable forest management (Bergeron et al. 2002, Keane 2003, Perera et al. 2004, Perera and Cui 2009). However, a forest fire regime is difficult to study because it not only has many aspects, including fire frequency/cycle/return interval, fire size distribution, burn probability, and severity, but also most if not all of those aspects have three dimensions – stochastic, spatial, and temporal – as shown in Figure 1.

While empirical approaches of studying forest fire regimes can help to explain what happened in the past, they do not provide adequate knowledge and guidance to explore what could happen or what will happen, and at what probability. As well, empirical approaches do not account for the stochasticity of forest fire regime and cannot be used to describe spatial and temporal variation at high resolution. The scope of forest fire knowledge acquired using such approaches amounts to a single point, i.e., the origin in the three dimensional space of forest fire regime (Figure 1).

To better understand the nature of fire regime both in general and for a specific forest landscape, the dynamic characteristics of the associated processes need to be addressed for all three dimensions. Therefore, strategic studies of forest fire regime in boreal forests, which involve large areas and long planning periods, require consideration of not only the stochasticity but also the potential spatial and temporal variation.

Simulation modelling is a relatively new approach for forest fire regime analysis. However, this approach has resulted in models that can be used to address various what-if and/or if-then questions asked by forest researchers and land managers. Some of these models, in particular those that simulate forest fires mechanically, are spatio-temporally explicit, are process-based, and can be used to explore more than one dimension of forest fire regimes (Keane 2003, Keane et al. 2004, Perera and Cui 2009, Perera et al. 2009). Therefore, simulation modelling has become very important in forest fire regime research.
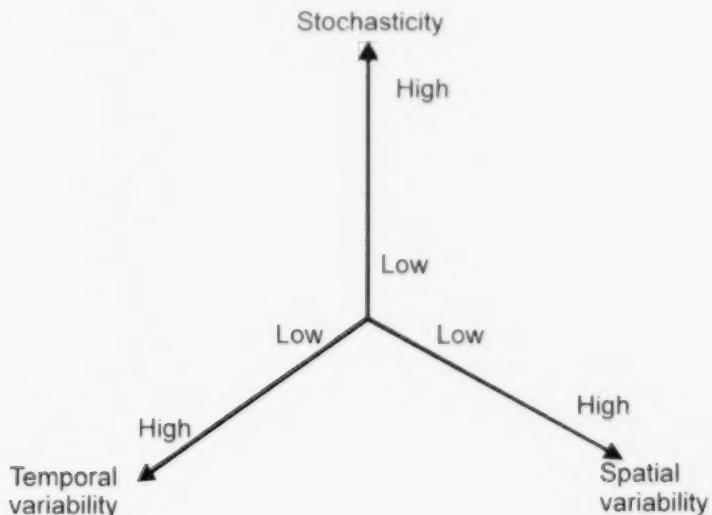
Figure 1. Schematic of the three dimensions of a forest fire regime.

BFOLDS is a spatially explicit model that simulates forest fire processes and forest succession over very large areas and long timeframes. It combines a mostly process-based fire module and an empirical forest succession module. As well, BFOLDS is a stochastic simulation model that is designed to capture the variability associated with forest fire regimes (for details see Perera et al. 2008).

This report is the third in a series: The first (Perera et al. 2008) describes the BFOLDS model – its principles, logic, and assumptions. The second (Ouellette 2008) is a user's guide that describes the use of the BFOLDS software package. This third report demonstrates the use of BFOLDS in forest fire regime analysis and potential applications of the model. The study area, user assumptions, simulation design, and fire regime indicators used here are examples as are the simulation study results and subsequent analyses. The focus of the case study is not so much what the fire regime is in the study area but rather how BFOLDS can be used in forest fire regime analysis. Also, to avoid duplication and to focus solely on an application of BFOLDS, we do not provide detailed descriptions of how BFOLDS works. We assume that the readers of this report are familiar with the report by Perera et al. (2008) that describes the principles, model assumptions, user assumptions, and includes detailed descriptions of model algorithms.

In this case study, we used BFOLDS to explore the overall forest fire regime as well as its characteristics in all three dimensions in a sample study area. We considered all major aspects of a forest fire regime except fire severity. These aspects included fire cycle/frequency/return interval, fire size distribution, and burn probability as well as indicators that were used to track forest dynamics such as forest cover type, age, and composition. The goal of this report is to present a simulated fire regime for the study area and to demonstrate how to model, present, and analyze boreal forest fire regimes using BFOLDS. Therefore, the emphasis of this case study is not so much the ecological aspects of a forest fire regime in the study area but more the methods and approaches for exploring fire regime using BFOLDS.

Methods

Simulation model

BFOLDS is a spatially explicit model that simulates forest fire processes and forest succession in a very large area (millions of hectares) over a long period (decades to centuries). It consists of a mostly process-based fire module and an empirical forest succession module. BFOLDS is also a stochastic simulation model, designed to capture the variability associated with forest fire regimes that results from fire ignition (number of fires and location and timing of each fire), fire extinguishment, and forest succession (with and without fire disturbance). The process-based fire simulation module means that BFOLDS mechanistically simulates processes of fire ignition, fire spread, and fire extinguishment as a function of fire weather, topography, and fuel patterns. Its raster-based fire growth sub-module is based on the Canadian Forest Fire Behaviour Prediction (FBP) system (Forestry Canada Fire Danger Group 1992) and Canadian Forest Fire Weather Index System (Van Wagner and Pickett 1985). BFOLDS simulates multiple fire events on a given landscape at 1 ha resolution and in continuous time, using spatial data on fuel types, weather, and topography.

BFOLDS assumes the number of successful ignitions for any simulation day follows a filtered Poisson process, with its mean derived from the daily ignition data of fire weather input. For example, if the number of ignitions for a fire weather day is m, that number is used as a mean to draw a number n from a probability distribution (Poisson if $m < 30$, otherwise normal), and the number of ignitions seeded for that simulation day will be n. These ignition points are positioned within a simulation landscape based on user-defined spatial biases. Seeded ignitions will succeed only if the fuel moisture at the location is above a threshold value. Fuel moisture is indicated by the duff moisture code (DMC), a Canadian fire weather index that defines a numeric rating of the average moisture content of loosely compacted fuel (Van Wagner and Pickett 1985). Once fire ignites in a cell, it can spread to 32 neighbouring cells in a 9 by 9 cell window. The spread time to neighbouring cells is calculated using the FBP system based on prevailing weather conditions and the fuel types in those cells (Perera et al. 2008). Fire spread stops when DMC values fall below a threshold, which is set by the user based on local knowledge. When fire spread stops for all cells within a fire perimeter, the fire is considered extinguished. BFOLDS thus simulates ignition, spread, and extinguishment of multiple fires simultaneously in a large landscape, guided by streams of daily fire weather during a fire season in a landscape with a spatial configuration of forest fuel types and topography.

In BFOLDS, long-term forest succession is simulated stochastically at 1 ha resolution, based on a time-dependent Markov chain, using spatial data on forest cover composition, forest age, and site characteristics. The forest cover changes probabilistically with time during simulations, either due to ageing and/or due to fire disturbances and subsequent succession.

For further details about simulations of fire growth and forest succession in BFOLDS see Perera et al. (2008).

Case study area

The study area used to illustrate the potential uses of BFOLDS is in Ontario's boreal forest region. Based on geo-climatic patterns it was classified as ecoregion 3W by Hills (1959) (Figure 2). The study area is 8.8 million ha, of which 7.4 million ha is forested. It is characterized by a cold-dry climate; well drained soil, rolling terrain interspersed with lakes, and is dominated by conifer and mixed-conifer forest (Rowe 1972). Major species occurring in the area include black spruce (Picea mariana [Mill.] B.S.P.), jack pine (Pinus banksiana Lamb.), trembling aspen (Populus tremuloides Michx.), birch (Betula spp.), and balsam fir (Abies balsamea [L.] Mill.) (Figure 3). Forest cover types codes used throughout the report are described in Table 1. Non-burnable forest cover types are not shown in Figure 3 and Table 1.

Figure 2. The case study area encompassed ecoregion 3W in northwestern Ontario north of Lake Superior.
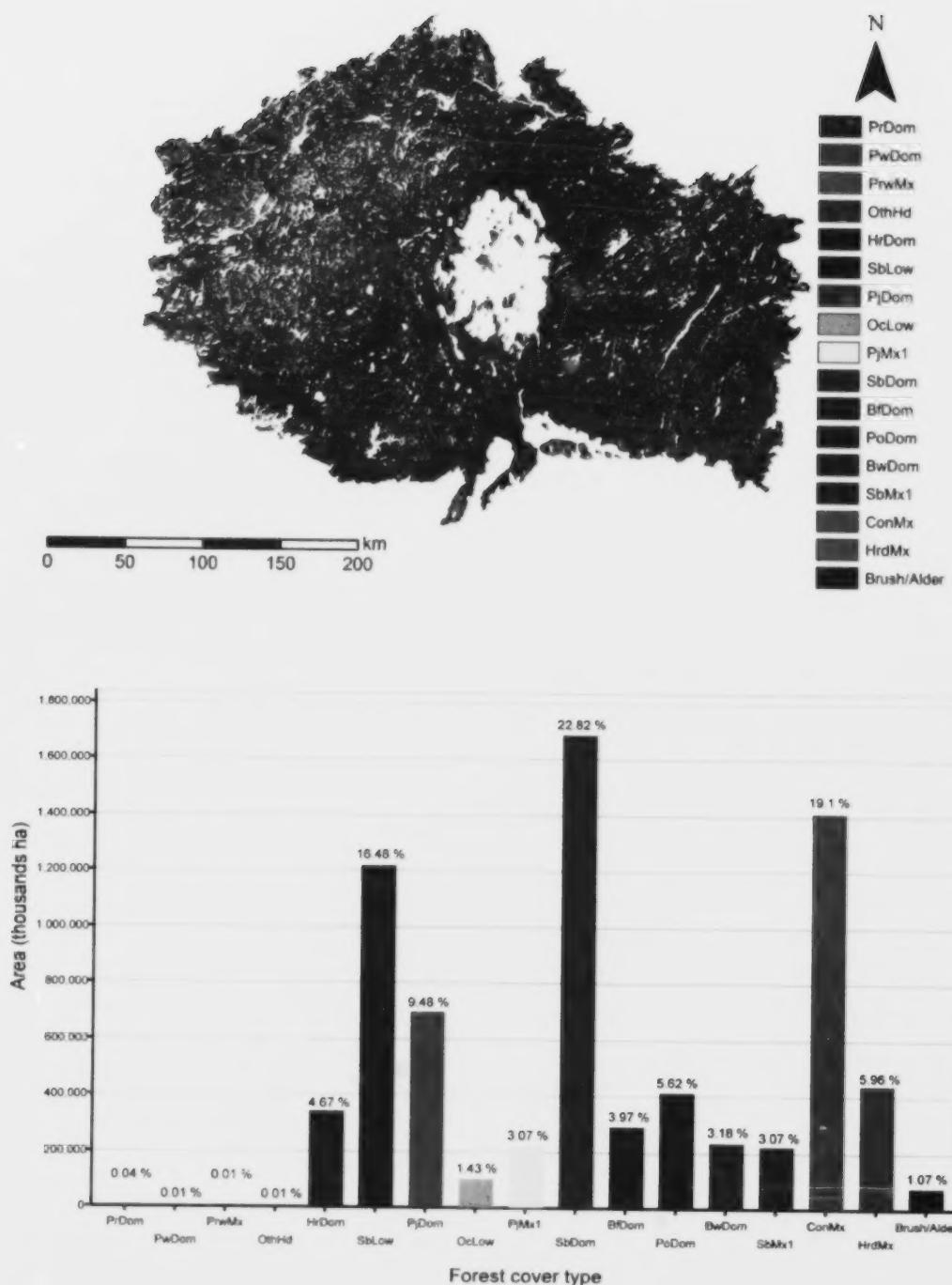
Figure 3. Present-day spatial distribution (a) and area (b) of forest cover types in the case study area. Forest cover type codes are defined in Table 1.

Table 1. Codes used to identify forest cover types for the case study.
The codes are forest units names used in Ontario's Northwest Region
(from Elkie et al. 2007).

Code	Description of forest cover
PrDom	Red pine dominated
PwDom	White pine dominated
PrwMx	Red and white pine mixedwood
OthHd	Other hardwood
HrDom	Hardwood dominated
SbLow	Lowland black spruce
PjDom	Jack pine dominated
OcLow	Other lowland conifer
PjMx1	Jack pine mixed wood
SbDom	Black spruce dominated
BfDom	Balsam fir dominated
PoDom	Poplar dominated
BwDom	White birch dominated
SbMx1	Black spruce mixedwood
ConMx	Conifer mixed
HrdMx	Hardwood mixedwood
Brush/Alder	Brush/Alder

The primary natural disturbance regime in the case study area is periodic stand-replacing fires, with insects, forest diseases, and wind throw also occurring (Perera et al. 1998). In addition, forest harvesting occurs in the area and fires are suppressed (OMNR 2004). Therefore, the input data used reflect these disturbances.

Simulation study design

For the case study, the simulation period was 200 years. To capture the variability in the fire regime, thirty simulations were run, each starting with the same input data and user assumptions. We used the present-day land cover information (such as forest composition and age) as the year-zero state to seed subsequent forest succession.

During simulation runs, the location and time of each fire were documented, providing the base for many spatio-temporal summaries. To allow fires that could originate outside to spread into the case study area, we added a 20-km-wide external buffer. Regardless of their origin (study area or buffer) ,the extents of fires within the buffers were eliminated from subsequent data analyses. As well, all fires that ignited in the buffer but did not spread into the study area were excluded. For example, for the three fires shown in Figure 4, fire A spans both the study area and buffer, fire B is completely within the buffer, and fire C is completely within the study area. In this example, fire A is counted but only Ain, the portion that falls within the study area is included, and Aout is not; fire B is not counted; fire C is counted and all of its area is included in the analyses.
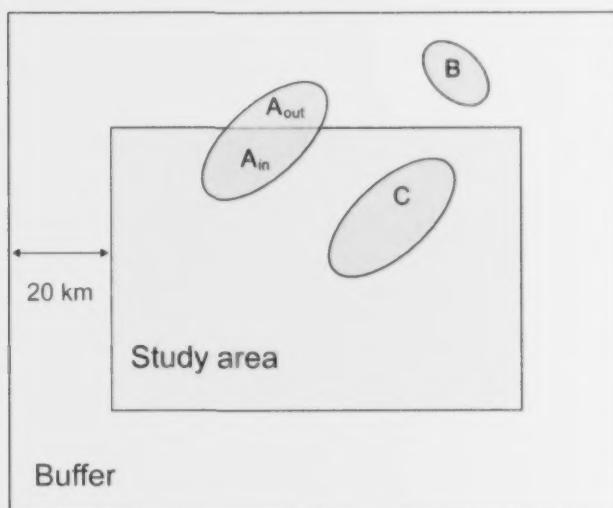
Figure 4. A hypothetical example of a study area with its buffer, illustrating the criteria defining simulated fires (number and area) included in this study: Fires A and C are counted, B is not; area of fires A_{in} and C are included, A_{out} and B are not.

User assumptions and input data

BFOLDS has explicit model premises and assumptions that comprise its logical foundation but it also requires user assumptions that define the specific simulation scenarios. In BFOLDS, all simulation processes of fire events and forest cover transition are conducted at 1 ha raster resolution. In the model, fires can ignite if a 1 ha cell has burnable fuel type and only while the DMC value of a cell is above a threshold, in this case 20. Further details about BFOLDS user assumptions are provided by Perera et al. (2008).

Any weather data that meet the input requirements (i.e., content and format) can be used with BFOLDS. To account for the uncertainty of knowledge of fire weather including the daily number of lightning-caused fire ignitions, we used the 42-year history of daily weather records (1963-2004) in this case study. For each simulation year, a historical weather year was randomly selected, while maintaining the natural sequence of days within each year. Daily weather data were expanded to hourly weather data to model fire growth using the algorithm described by Perera et al. (2008). The simulated daily number of fires was associated with each day of the selected weather year as described below.

For the purpose of this case study, we assumed that fires spread only while the value of DMC is above a threshold, which varied randomly up to 10% during a simulation day. The threshold value selected was 20±2 (based on regional expert opinion). Further, we arbitrarily assumed that a cell was burned if the fire intensity was ≥150 kW m^{-1}, which defines a stand-replacing fire. Once a cell burned, we assumed all fuel in that cell was consumed and its forest cover destroyed. Burned cells cannot re-burn in the subsequent 10 years. Forest succession due to ageing in the absence of stand-replacing fires or following destruction of forest cover by fire was guided by forest succession rule sets compiled by Ride et al. (2004), and subsequently modified by Elkie et al. (2007). Forest fuel classification (forest resource inventory groupings converted to FBP fuel classes) followed rules specified by Forestry Canada Fire Danger Group (1992) and Taylor et al. (1988), subsequently modified by Elkie et al. (2007).

All spatial data sets used in this simulation study were those constructed and regionally calibrated as described by Elkie et al. (2007) to support the development of the Ministry of Natural Resources' forest management guide (http://www.mnr.gov.on.ca/en/Business/Forests/1ColumnSubPage/STEL02_164558.html).

Spatial input data

Spatial data used in the simulation study are summarized in tables 2 and 3 and figures 3, 5, 6, and 8. In the broadest sense, input data may also be viewed as user assumptions. Forest cover types (Figure 3) were designated by forest units used in Ontario's Northwest Region (Elkie et al. 2007; Table 1). Forest age was defined as time since the previous burn, measured in years. Where forest age data were not available (i.e., Wabakimi area), forest age was assigned a value of 60 (as per Elkie et al. 2007), hence the relatively high frequency of that age class as shown in Figure 5.

**Table 2**. *Spatial data used as BFOLDS input for the case study.*

Data	Data conversion	Data source
Forest cover type (Figure 3) Forest age (Figure 5)	Forest Unit classification rules (Elkie et al. 2007)	1:20,000 Forest Resources Inventory of Ontario
Soil moisture Soil nutrient	Forest Unit classification rules (Elkie et al. 2007)	1:250,000 Ontario Land Inventory
Ecozones (Figure 6)	Forest Unit classification rules (Elkie et al. 2007)	2002 version of Ontario's ecoregion map
Latitude and longitude	ArcGIS functions	2002 version of Ontario's ecoregion map
Slope Slope aspect	ArcGIS functions	DTED digital elevation model (100 m) from http://geobase.ca
Landscape boundary	ArcGIS function	1:20,000 Forest Resources Inventory of Ontario
Ignition biasing pattern (Figure 8)	User-defined algorithm (see *Fire ignition pattern* section)	Daily weather data from multiple weather stations for 1963-2004 (point data) from OMNR historical fire weather archive

**Table 3**. *Spatial data that can be generated within BFOLDS.*

Data	Data conversion	Data source
Fine fuel moisture code[1] Duff moisture code Drought code Initial spread index Buildup index	Interpolated from point data and latitude and longitude using the interpolation algorithm of Flannigan and Wotton (1989)	Daily weather data from multiple weather stations for 1963-2004 (point data) from OMNR historical fire weather archive

[1]Fine fuel moisture code, duff moisture code, drought code, initial spread index, and buildup index are quantitative fire weather indices as defined in the Canadian Forest Fire Weather Index System (Van Wagner and Pickett 1985).
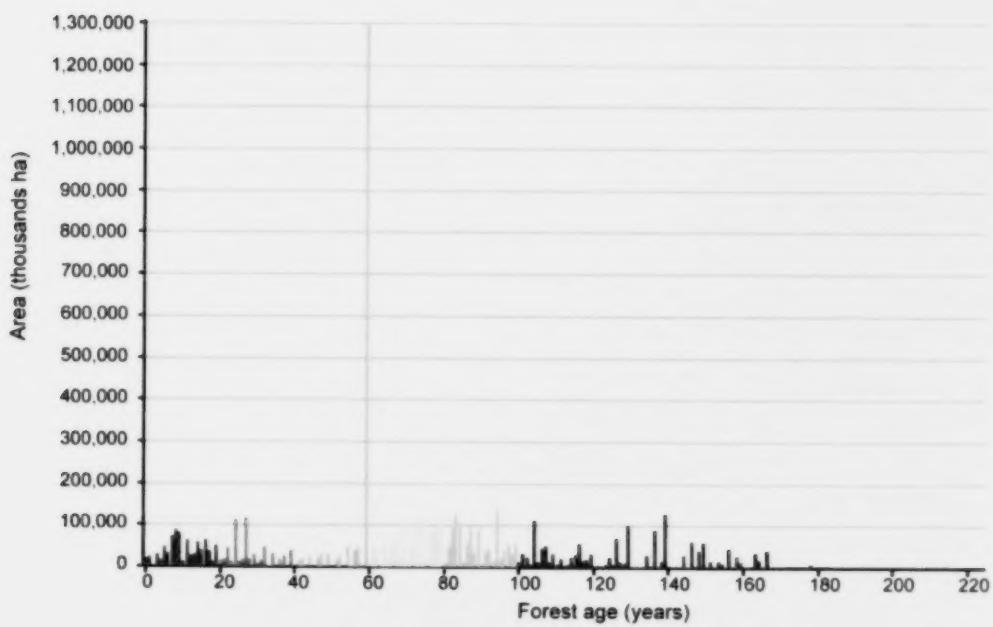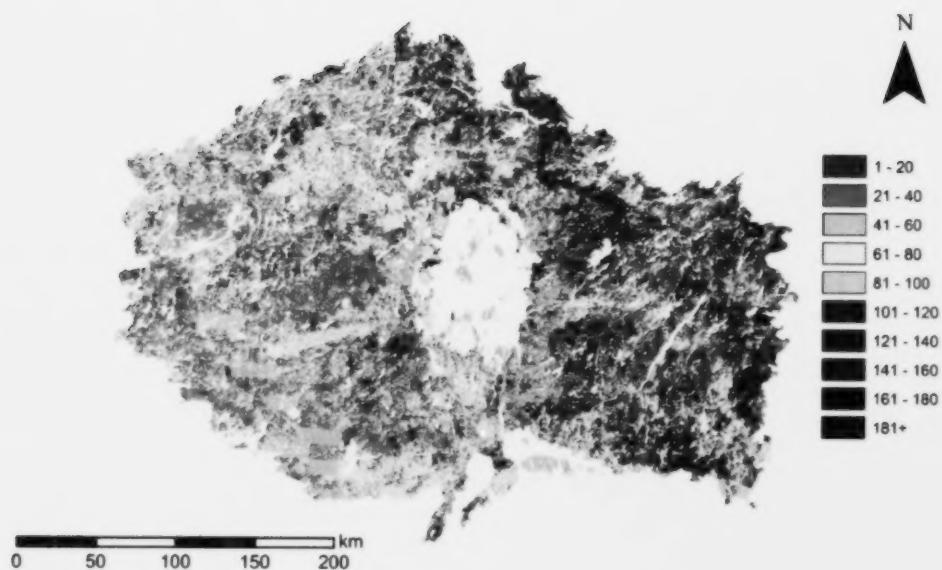
Figure 5. Present-day spatial distribution (a) and frequency distribution (b) of forest ages in the case study area. Note: The peak at age 60 is because areas lacking age data were assigned to that age class.
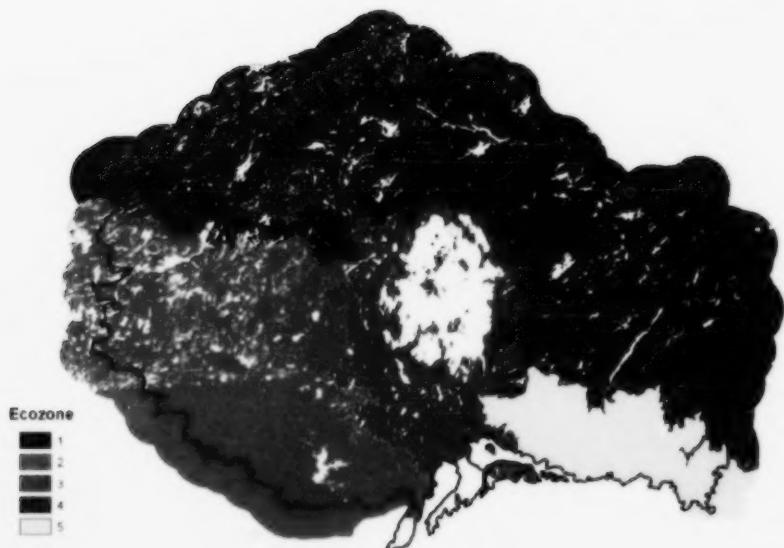
Figure 6. *Ecozones within the case study area. The black line is the study area boundary within the 20-km-wide buffer zone.*

Fire ignition pattern

To account for the uncertainty in knowledge of potential spatial patterns of lightning-caused fire ignitions, we assumed that fire ignition occurrence is spatially biased to patterns (Figure 7) recorded during the 42-year history of weather records. Steps to implement the spatial biasing were as follows:

First, we produced a raster grid of density of ignition, where density of ignition d_i at cell *i* was defined as:

$$d_i = \frac{N_i}{A_i} \quad (1)$$

where d_i is the density of ignition (number of fires per hectare), A_i is the forested area of the search window (one million ha in this study) with the centre at cell *i*, and N_i is the number fires that occurred during the 42-year period in the forested area of the search window. The ignition pattern was generated from point data based on equation (1). We then normalized the value of d_i using:

$$d_i' = d_i / d_{max} \quad (2)$$

where d_i' is the normalized density of ignition ranges from 0 to 1, d_{max} is the maximum of d_i ($i =1, 2, \ldots, N$), and *N* is the total number of forested cells in the study area.

From this, we extracted the ignition density map of the study area and the buffer (Figure 8).
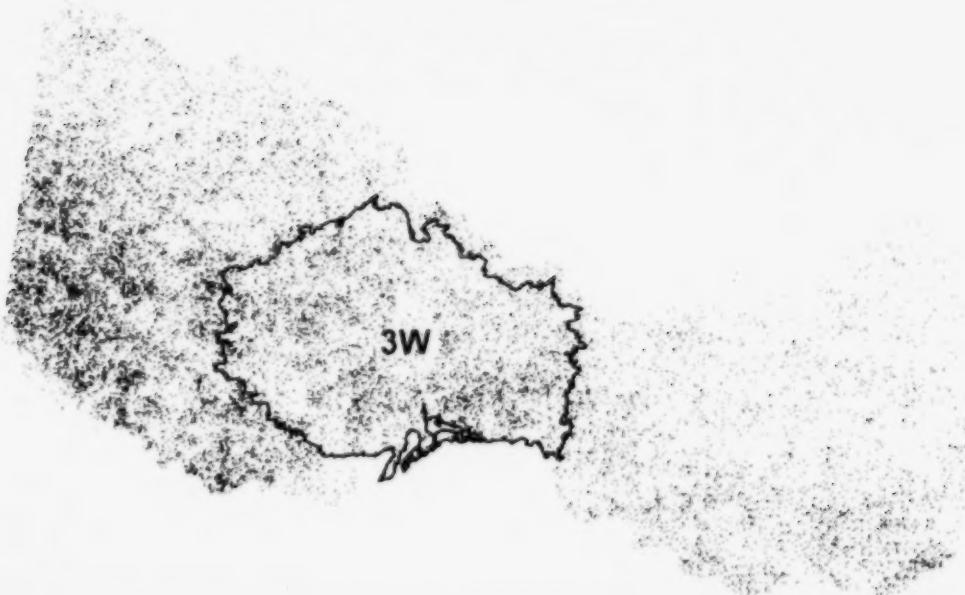
Figure 7. Locations of lightning-caused ignitions from 1963-2004 in an area of northwestern Ontario that includes the case study area (Source: DFOSS Fire Archive Access Database, Rob Luik, Information Management Specialist, Ministry of Natural Resources, Fire Management Section, 70 Foster Drive, Sault Ste. Marie, ON, (705) 945-6748).
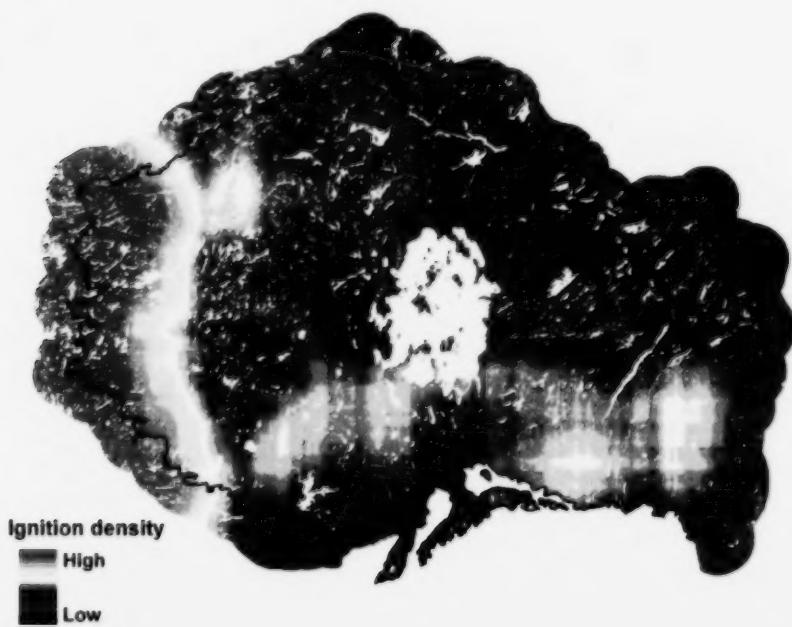
Figure 8. Ignition density map of ecoregion 3W (case study area with buffer) produced using data of lightning-caused fire ignitions during 1963-2004 (see Figure 7).

Second, fire locations were generated based on relative probability. A cell j (location) was randomly seeded in the raster grid, and a random number x ranging from 0 to 1 was generated. If x was less than d_i' (equation 2), location j was selected. If not, the above process (select location, generate random number x that ranges from 0 to 1), was repeated until x was smaller than d_i'.

The probability of each cell j was calculated as:

$$p_j = \frac{d_j}{\sum_{i=1}^{N} d_i} \quad (3)$$

where p_j is the probability of each cell j being selected once, d_j is the density of ignition at cell j, and N is the total number of forested cells in the study area. This process generated the biased fire ignition pattern used in the case study.

Fire regime indicators

We investigated many characteristics of the fire regime in the case study area by estimating not only the means but also their spatial, temporal, and random variability. We did not try to investigate all aspects of the fire regime. The indicators selected and described below are examples to show uses of BFOLDS in fire regime analysis. These included annual burn fraction (ABF), annual number of fires (ANF), fire return interval (FRI), and fire size distribution (FSD) based on the primary output of BFOLDS (Table 4).

Table 4. Primary output of BFOLDS for each 1-ha pixel and every simulation year.

Name	Description
Fire ID	The number assigned to a pixel that identifies a unique simulated fire
Fire intensity	Fire line intensity (kw m^{-1})
Forest age	Forest cover age (time since burn and canopy cover age separately)
Forest cover type	Forest cover composition

Indicators of overall variability

Several indicators were used to capture the characteristics of a fire regime over the entire landscape over the whole study period without accounting for their spatial and temporal aspects. They include the following:

A. Overall annual burn fraction is the fraction of average annual area burned over the total forested area during the simulation period, as a %:

$$ABF = \frac{Total\ area\ burned\ over\ the\ simulation\ period}{Number\ of\ years \times Total\ forested\ area} \times 100 \quad (4)$$

B. Annual burn fraction of age class a over the simulation period, as a %:

$$ABF_a = \frac{\sum_{k=1}^{Number\ of\ years} Total\ area\ of\ age\ class\ a\ burned\ in\ year\ k}{\sum_{k=1}^{Number\ of\ years} Total\ forested\ area\ of\ age\ class\ a\ in\ year\ k} \times 100 \quad (5)$$

where a is the age class code. We classified age into 10 categories: [0, 20], [21, 40], ..., [181, ∞]. The a values are 1, 2, ..., 10.

C. Annual burn fraction of forest cover type *c* over the simulation period, as a %:

$$ABF_c = \frac{\sum_{k=1}^{Number\ of\ years} Total\ area\ burned\ of\ cover\ type\ \ c\ in\ year\ k}{\sum_{k=1}^{Number\ of\ years} Total\ \ forested\ area\ of\ cover\ type\ \ c\ in\ year\ k} \times 100 \tag{6}$$

where *c* is the forest cover type.

D. Overall annual number of fires over the simulation period:

$$ANF = \frac{Total\ number\ of\ \ fires\ in\ the\ period}{Number\ of\ \ years\ in\ the\ period} \tag{7}$$

E. Fire return interval (FRI) over the simulation period was defined as the inverse of *ABF*, in years:

$$FRI = \frac{Number\ of\ \ years\ in\ the\ period \times Total\ \ forested\ area}{Total\ area\ burned} \tag{8}$$

where *total area burned* cannot be zero.

F. Forest fire size distribution

To show the FSD, we used cumulative density function and categorized fire size data. We divided the fire sizes into six categories as (0, 1], [1, 10], (10, 100], (100, 1,000], (1000, 10000], and (10000, ∞] ha, respectively, because of evidence that fire sizes in boreal forest are likely to follow power-law (Cui and Perera 2008).

Indicators of temporal variability

The temporal indicators were designed to capture the trends of fire regime over time without considering its spatial variation. They include the following:

A. Annual burn fraction by year ABF_t as a %, is defined as:

$$ABF_t = \frac{Total\ area\ burned\ at\ year\ t}{Total\ \ forested\ area} \times 100 \tag{9}$$

where *t* is the simulation year, t = 1, 2, ..., 200.

B. Annual number of fires at year *t*

$$ANF_t = Number\ of\ \ fires\ at\ year\ t$$

where *t* is the simulation year, t = 1, 2, ..., 200.

C. Age class composition or fraction of area for age class *i* at year *t* as a %, is defined as:

$$AC_{it} = \frac{Total\ area\ of\ age\ class\ i\ at\ \ year\ t}{Total\ \ forested\ area} \times 100 \tag{10}$$

where *i* is the age class code. We classified age into 10 categories: [0, 20], [21, 40], ..., [181, ∞]. The *i* values are 1, 2, ..., 10. *t* is the simulation year, t = 1, 2, ..., 200.

D. Cover type composition or fraction of area for forest cover type i at year t as a %, is defined as:

$$CT_{it} = \frac{Total\ area\ of\ cover\ type\ i\ at\ year\ t}{Total\ forested\ area} \times 100 \tag{11}$$

where i is forest cover type identification code and t is the simulation year, $t = 1, 2, \ldots\ldots, 200$.

Indicators of spatial variability

The spatial indicators were designed to capture the variations of fire regime in space without considering its temporal variation. They include the following:

A. Annual burn fraction at cell i (as a %) over the simulation period is defined as:

$$ABF_i = \frac{Number\ of\ times\ cell\ i\ burned}{Number\ of\ simulation\ years} \times 100 \tag{12}$$

where i is the cell identification number.

B. Conditional spatial forest fire size class distribution: Probability of cell i being burned by a fire of size class k (as a %) assuming that the cell is burned over the simulation period:

$$FSD_{con}\_P_{ik} = \frac{Number\ of\ times\ cell\ i\ is\ burned\ by\ fires\ of\ size\ class\ k}{Total\ number\ of\ times\ cell\ i\ burned} \times 100 \tag{13}$$

where i is the cell identification number and k belongs to [1, 10], (10, 100], (100, 1,000], (1000, 10000], and (10000, ∞] ha, respectively. We divided the fire size classes based on the assumption that fire sizes in boreal forest are most likely to follow power-law (Cui and Perera 2008).

C. Spatial forest fire size class distribution: Probability of cell i being burned by a fire of size class k (as a %) over the simulation period:

$$FSD\_P_{ik} = \frac{Number\ of\ times\ cell\ i\ is\ burned\ by\ fires\ of\ size\ class\ k}{Number\ of\ simulation\ years} \times 100 \tag{14}$$

where i is the cell identification number and k belongs to [1, 10], (10, 100], (100, 1,000], (1000, 10000], and (10000, ∞] ha, respectively. We divided the fire size classes based on the assumption that fire sizes in boreal forest are most likely to follow power-law (Cui and Perera 2008).

Notice that

$$FSD\_P_{ik} = ABF_i \times FSD_{con}\_P_{ik} \tag{15}$$

and

$$ABF_i = \sum_k FSD\_P_{ik} \tag{16}$$

Indicators of spatio-temporal variability

The spatio-temporal indicators are designed to capture all three dimensions of a forest fire regime: spatial, temporal, and stochastic.

A. Annual burn probability (ABP) at cell i over a N-year period p as a %, is defined as:

$$ABP_{ip} = \frac{\sum_{j=1}^{Number\ of\ replicates} \dfrac{Number\ of\ times\ cell\ i\ burned\ over\ simulation\ period\ p\ of\ N_p\ years}{N_p}}{Number\ of\ simulations} \times 100 \quad (17)$$

where N_p is the number of years in the period p, i is the cell number, and t identifies the N_p-year period. In this case study, categories for p, measured in years, are [1, 50], [51,100], [101, 150], and [151, 200], respectively. The p values are 1, 2, 3, and 4.

B. Annual burn probability at cell i at year t as a %, is defined as:

$$ABP_{it} = \frac{Number\ of\ times\ cell\ i\ burned\ at\ year\ t}{Number\ of\ simulations} \times 100 \quad (18)$$

where i is the cell number and t is the simulation year; $t = 1, 50, 100, 150,$ or 200.

C. Probability of forest cover type k at cell i at year t as a %, is defined as:

$$CTP_{ikt} = \frac{Number\ of\ times\ cover\ type\ k\ appears\ at\ cell\ i\ at\ year\ t}{Number\ of\ simulations} \times 100 \quad (19)$$

where i is the cell number, k is the forest cover type, and t is the simulation year; $t = 50, 100, 150,$ or 200.

D. Probability of forest age k or older reached at cell i at year t as a %, is defined as:

$$AgeP_{ikt} = \frac{Number\ of\ times\ age \geq k\ at\ cell\ i\ at\ year\ t}{Number\ of\ simulations} \times 100 \quad (20)$$

where i is the cell number, k is the forest age, and t is the simulation year; $t = 50, 100, 150,$ or 200; $k = 50, 100, 150,$ or 200.

E. Probability of forest cover type m of forest age k or older reached at cell i at year t as a %, is defined as:

$$AgeP_{imkt} = \frac{Number\ of\ times\ cover\ type\ m\ at\ age \geq k\ at\ cell\ i\ at\ year\ t}{Number\ of\ simulations} \times 100 \quad (21)$$

where i is the cell number, m is the forest cover type, k is the forest age, and t is the simulation year; $t = 50, 100, 150,$ or 200.

Simulation Results

We describe the results of the case study, emphasizing how to model, present, and thus analyze boreal forest fire regime in general, rather than the forest fire regime in the study area per se. The aim is to show how BFOLDS can be used in forest fire regime analysis or related studies.

Overall fire regime

We used ABF to evaluate the area burned in the case study area. Based on the 30 simulations, the average ABF over 200 years was 0.97%. The ABFs varied from 0.83% to 1.55% among the simulations as shown in Figure 9. For the same period and number of simulations, the average ANF was 49.4. Average ANF varied from 43.1 to 55.2 among simulations (Figure 10). The FRI varied from 64 to 121 years among simulations with an average of 105 years (Figure 11).
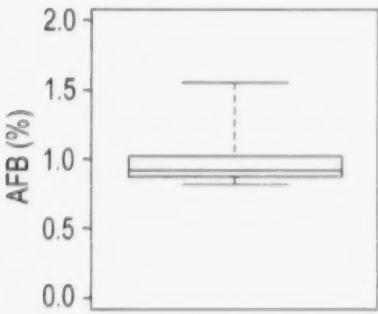
Figure 9. Average annual burn fraction (ABF) in the case study area for a 200-year period (n = 30 simulations). Box indicates the interquartile range, middle line the median, and whiskers the min-max values.
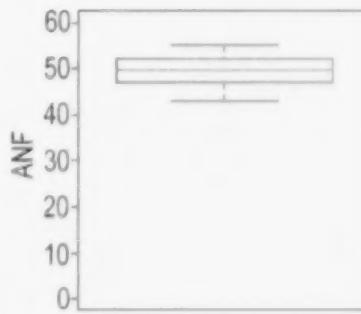
Figure 10. Average annual number of fires (ANF) in the case study area for a 200-year period (n = 30 simulations). Box indicates the interquartile range, middle line the median, and whiskers the min-max values.
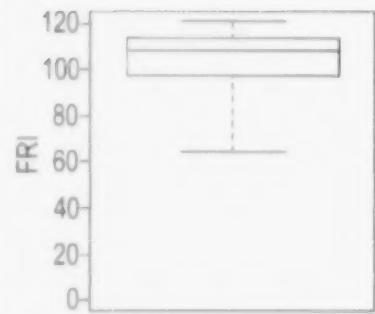
Figure 11. Fire return interval (FRI) in the case study area for a 200-year period (n = 30 simulations). Box indicates the interquartile range, middle line the median, and whiskers the min-max values.

Annual burn fractions differed among forest age classes as shown in Figure 12. Annual burn fraction in age class (0, 20] was significantly lower than in most other age classes because BFOLDS is set up so that an area cannot re-burn within 10 years. Among the 30 simulations, relatively large variation was evident within age classes.

Similarly, ABFs differed among forest cover types. Cover types were ranked from the smallest to the largest average ABF as shown in Figure 13. Overall, the conifer or conifer-dominated mixedwood forest cover types had higher ABFs than deciduous and lowland cover types. Among the 30 simulations, relatively large variation is evident within forest cover types.
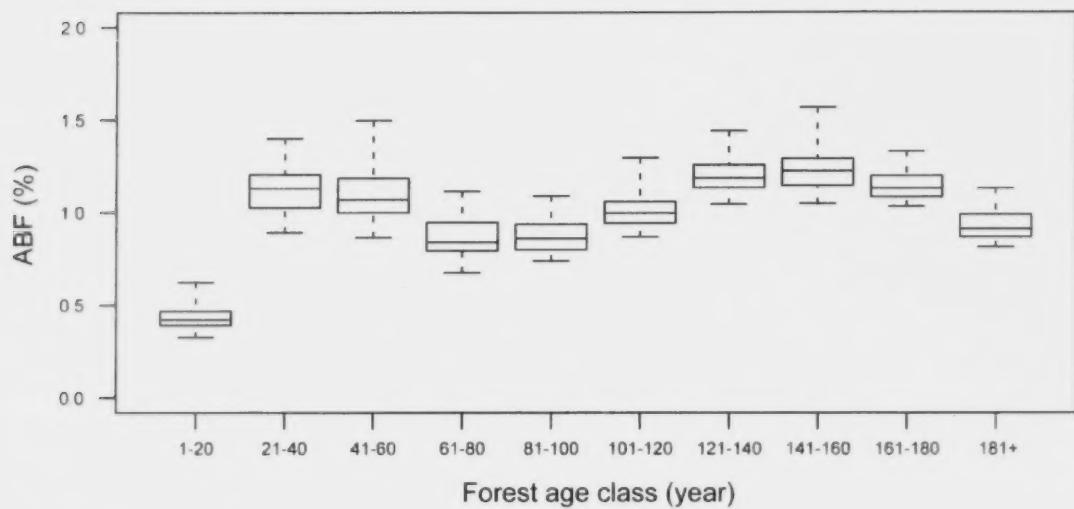
Figure 12. *Average annual burn fraction (ABF) by age class in the case study area for a 200-year period (n = 30 simulations). Boxes indicate the interquartile range, middle lines the median, and whiskers the min-max values.*
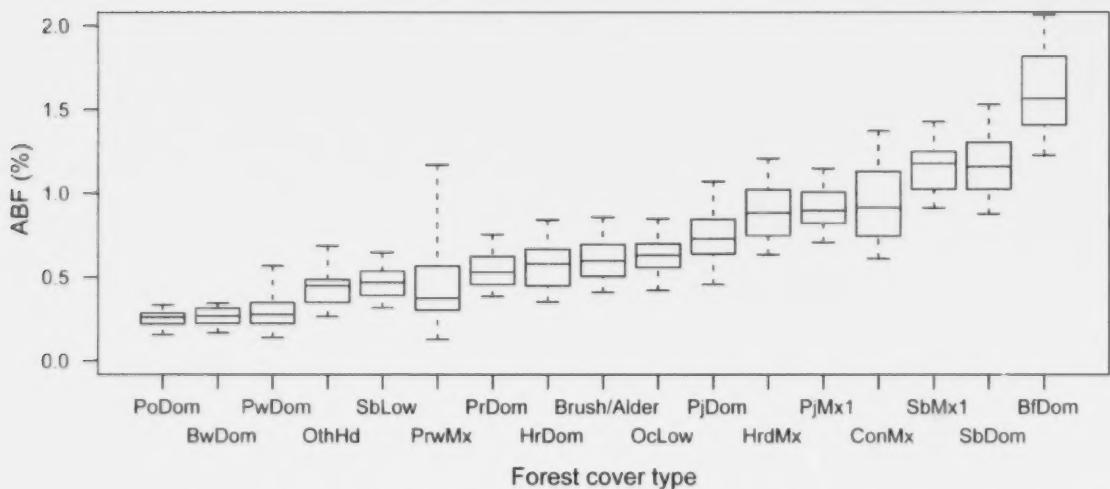
Figure 13. *Average annual burn fraction (ABF) by forest cover type (ordered by increasing %) in the case study area for a 200-year period (n = 30 simulations). Boxes indicate the interquartile range, middle lines the median, and whiskers the min-max values. Cover type codes are defined in Table 1.*

Forest fire size distribution

The cumulative density functions of fire sizes for the 30 simulations are shown in Figure 14. We also classified the fires into six size classes: (0, 1], (1, 10], (10, 100], (100, 1,000], (1,000, 10,000], and (10,000, ∞] ha. Figure 15 shows the size class distributions of fires in the case study area over 200 years for 30 simulations. Large variations within each size class are evident among the simulations.

Temporal trends of fire regime

The average ABFs of the 30 simulations are shown for 200 simulation years in Figure 16. Year to year variation was substantial and the general trend was a gradual increase in ABF over time. Within-year variability of ABF was even higher, with minimum ABFs mostly zero or near zero and maximum ABFs much larger than the mean (Figure 17). These within-year variations were significantly higher than those for overall ABF, as described in the section on overall fire regime above.

The average ANF from the 30 simulations is shown in Figure 18. Year to year variation was high and the general trend was that ANF decreased slightly over time. Figure 19 shows high within-year variability in ANF. The minimum ANFs were mostly zero or very small, while the maximum ANFs were much larger than the means. These within-year variations were significantly higher than those for overall average ANF, as described in the section on overall fire regime above. The increase in ABF and the decrease in ANF over time indicate that average fire size increased over time.
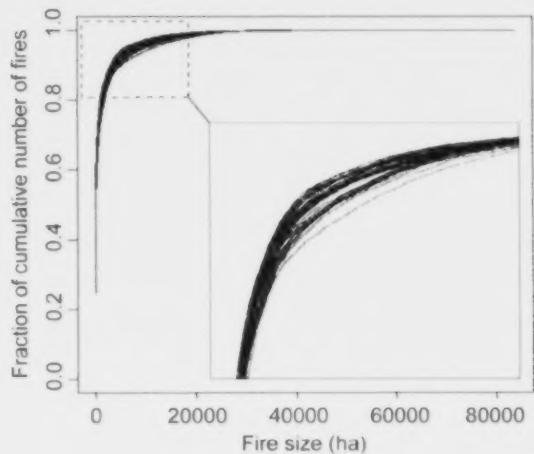

Figure 14. *The cumulative density functions of fire sizes in the case study area for a 200-year period (n = 30 simulations).*
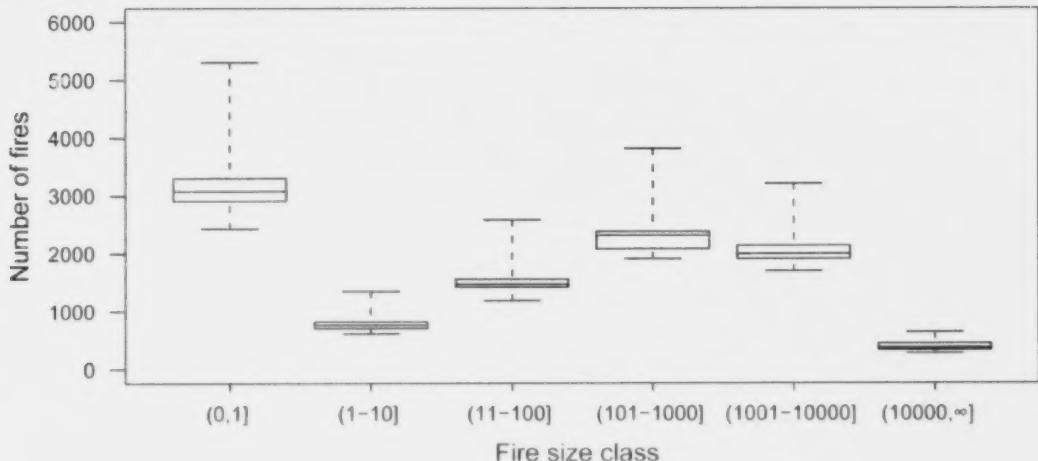

Figure 15. *Size class distributions of forest fires in the case study area for a 200-year period (n = 30 simulations). Boxes indicate the interquartile range, middle lines the median, and whiskers the min-max values.*
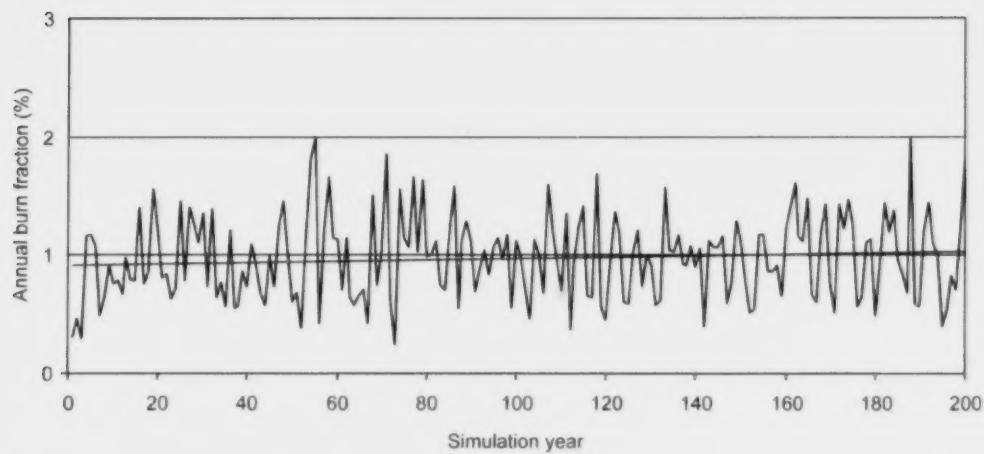
Figure 16. Average annual burn fractions in the case study area over 200 simulation years (n = 30 simulations).
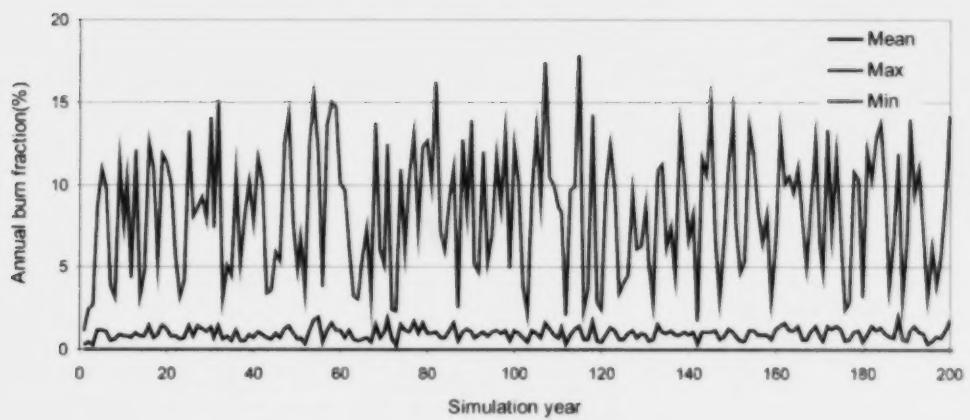
Figure 17. Average, maximum, and minimum annual burn fractions in the case study area over 200 simulation years (n = 30 simulations). Note: The minimum annual burn fractions are near zero so the line almost coincides with the x-axis.
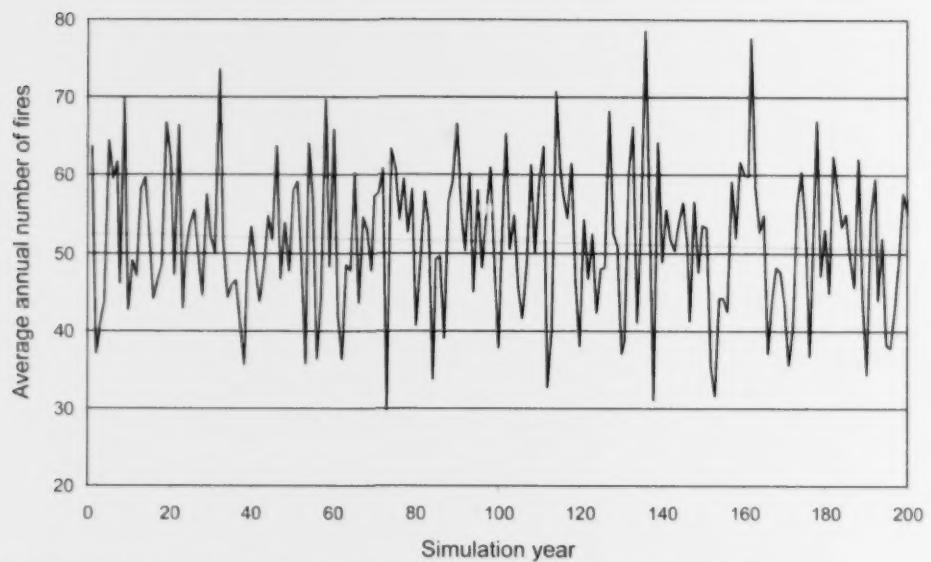
**Figure 18.** Average annual number of fires in the case study area over 200 simulation years (n = 30 simulations).
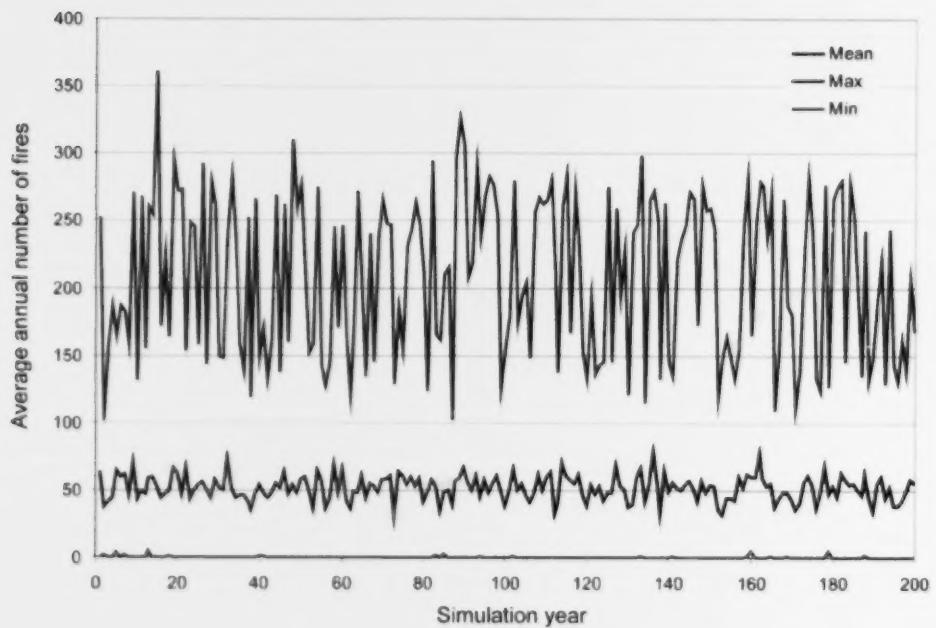
Figure 19. Average, maximum, and minimum annual number of fires in the case study area over 200 simulation years (n = 30 simulations). Note: The minimum annual numbers of fires are near zero so the line almost coincides with the x-axis.

The change in forest age class composition over time is shown in Figure 20. The composition values for year one to 200 were averages from the 30 simulations. Figure 20 shows only the temporal trend for forest age composition (mean). However, for each age class considerable variation occurred within each year. For example, Figure 21 shows the variations in proportions for age classes 1-20, 101-120, and 181-∞ over the 200 simulation years. A decline in one age classes always corresponds with an increase in the neighbouring older age class. This results from the aging of a large area in the 60-year age class (where forest age data were not available, forest age was assigned a value of 60 as described in the Methods section) at the start of the simulation year. The magnitude of variation increased with time and then stabilized with younger age classes stabilizing before the older age classes.

The change in forest cover composition over time is shown in Figure 22. The composition for year zero was based on the input forest cover data. Composition values for year one to 200 were average outputs from the 30 simulations. Again, Figure 22 shows only the temporal trend for forest cover types. Within-year variation was considerable for each forest cover type. For example, Figure 23 shows the variations in proportions for forest cover types SbDom and ConMx (See Table 1 for code definitions) over the 200 simulation years. Variability differed among forest cover types; in this case that of SbDom was more variable than that of ConMx.
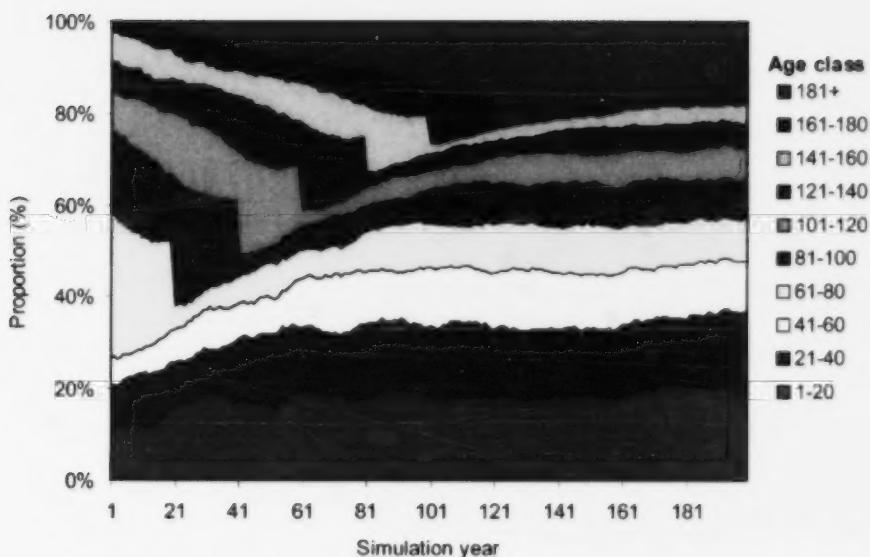

Figure 20. Average proportions of forest age classes in the case study area over 200 simulation years (n = 30 simulations).

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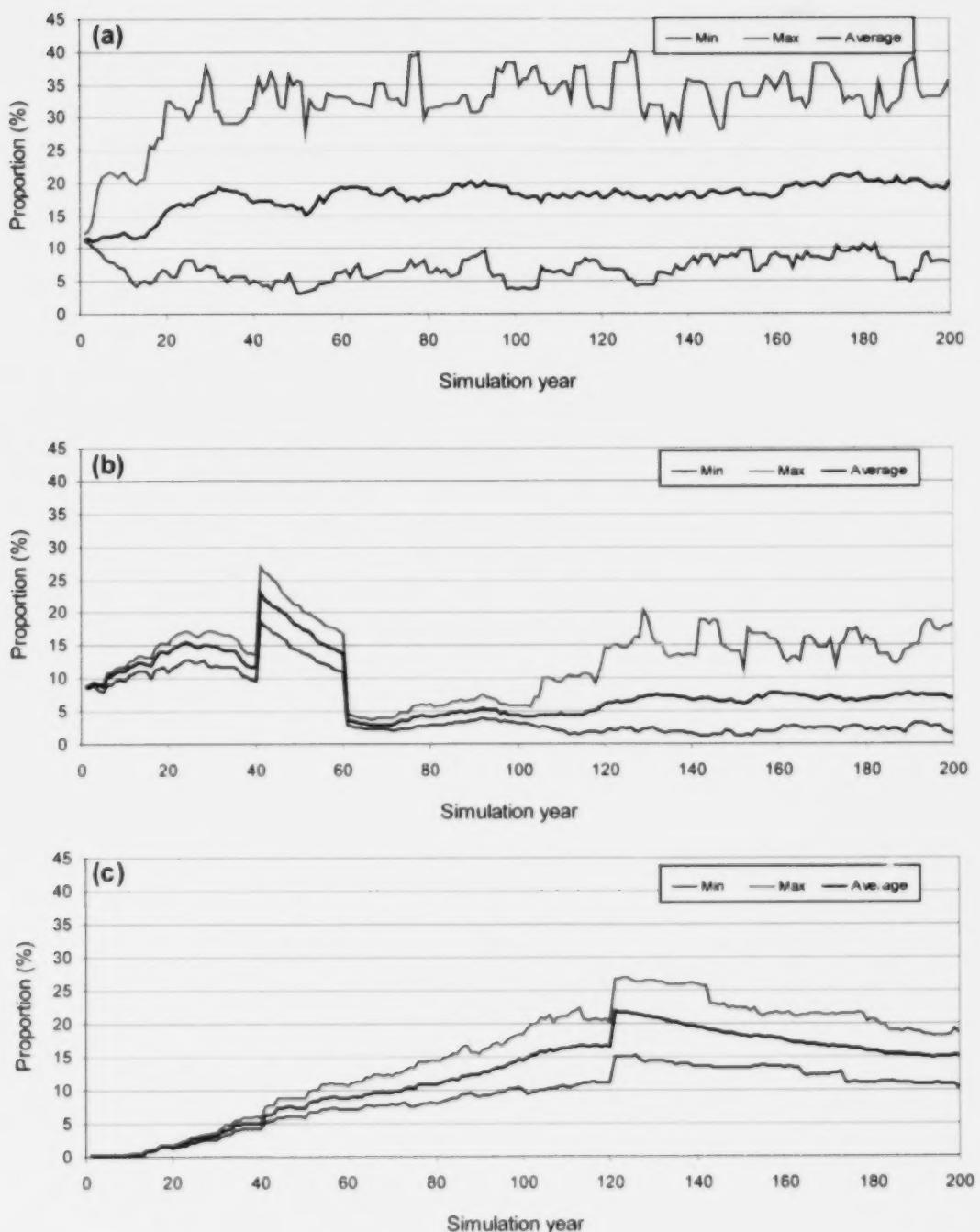
Figure 21. Changes in proportions of forest age class in the case study area for age classes 1-20 (a), 101-120 (b), and 181 - ∞ (c) over the 200 simulation years (n = 30 simulations).
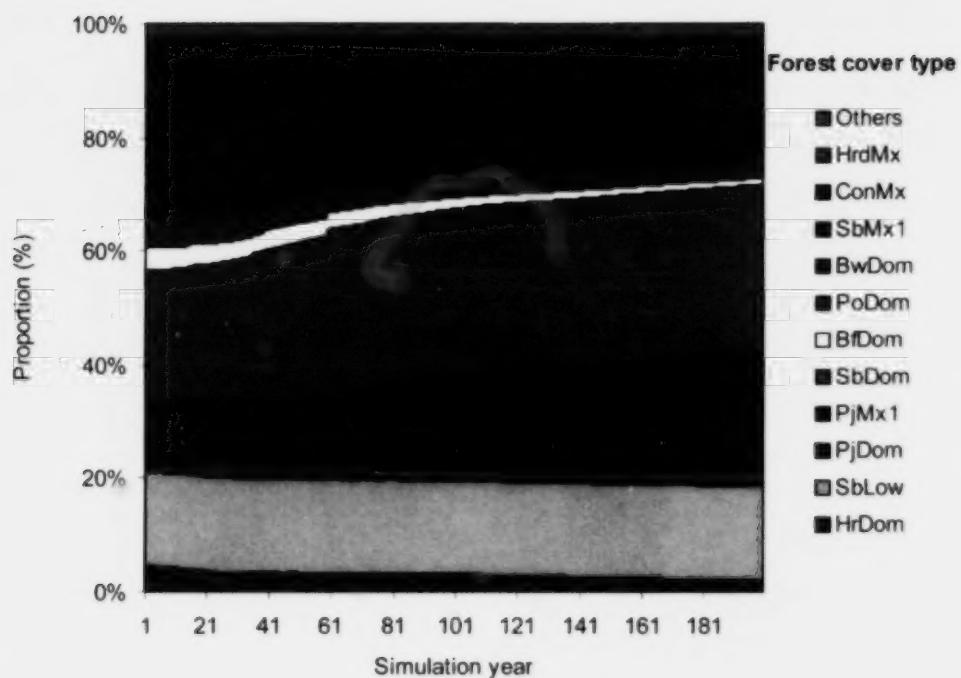
Figure 22. *Average proportions of forest cover types in the case study area over 200 simulation years (n = 30 simulations). Forest cover types are defined in Table 1.*
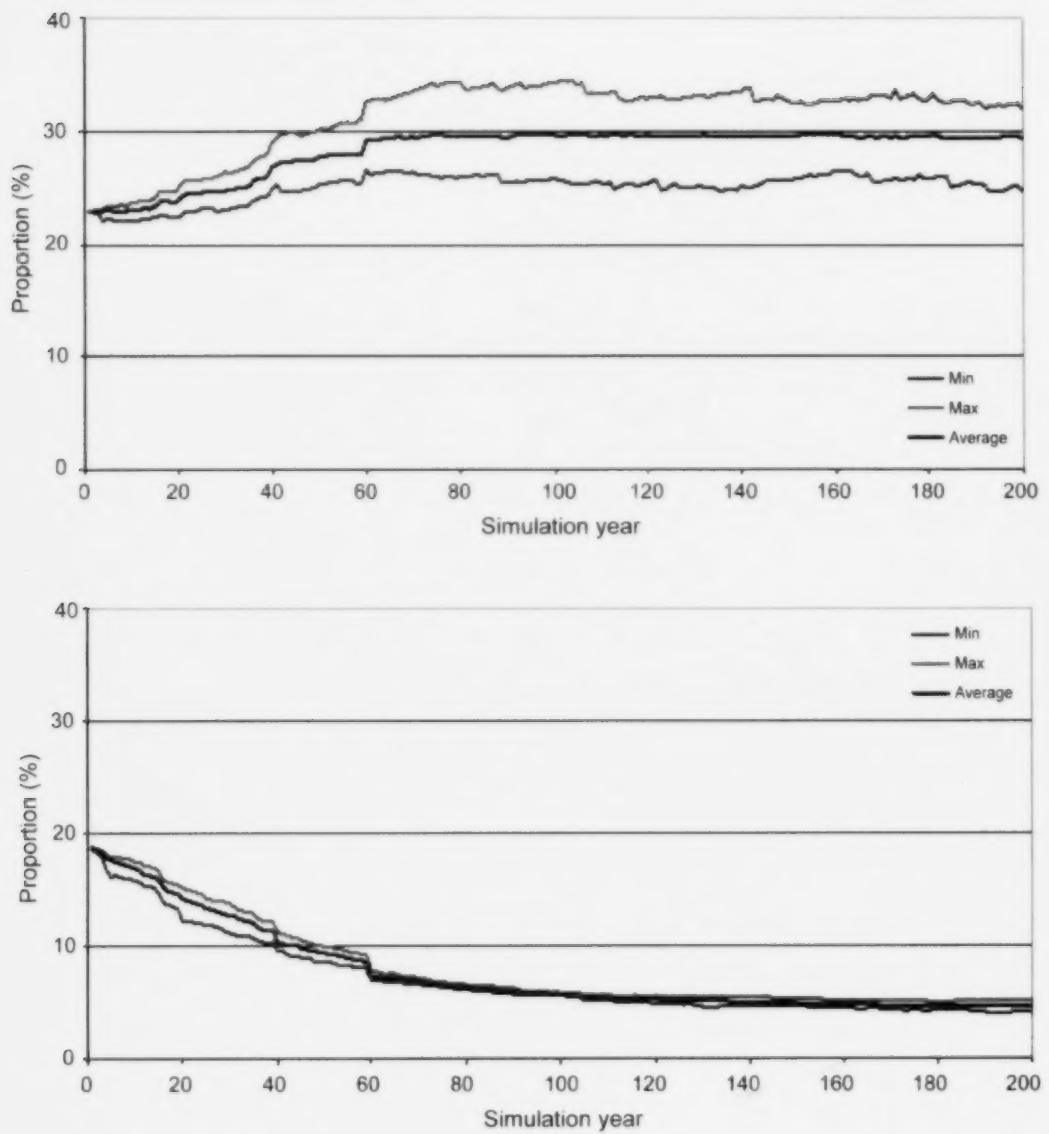
Figure 23. Changes in proportions of forest cover types SbDom (a) and ConMx (b) over the 200 simulation years (n = 30 simulations).

Spatial patterns of fire regime

We analyzed the spatial pattern of the fire regime in the case study area over the 200-year period based on ABF and fire size class distributions.

Following the mathematical definition provided in the Methods section, the ABF can also be understood as average annual burn probability (ABP) of the case study area over the 200-year period. As Figure 24 shows, ABF or ABP varied greatly in space. The frequency distribution of the average ABF is shown in Figure 25. Variability in ABFs at each location was high, as shown in Figure 26 as well as the frequency distribution of the range of variation of the average ABF in Figure 27. The range of variation at a cell is defined as the maximum ABF minus the minimum ABF (with the same unit as the ABF). Overall, the range of variation is higher than the absolute value of ABF, indicating high uncertainty about spatial pattern of average ABF or ABP.
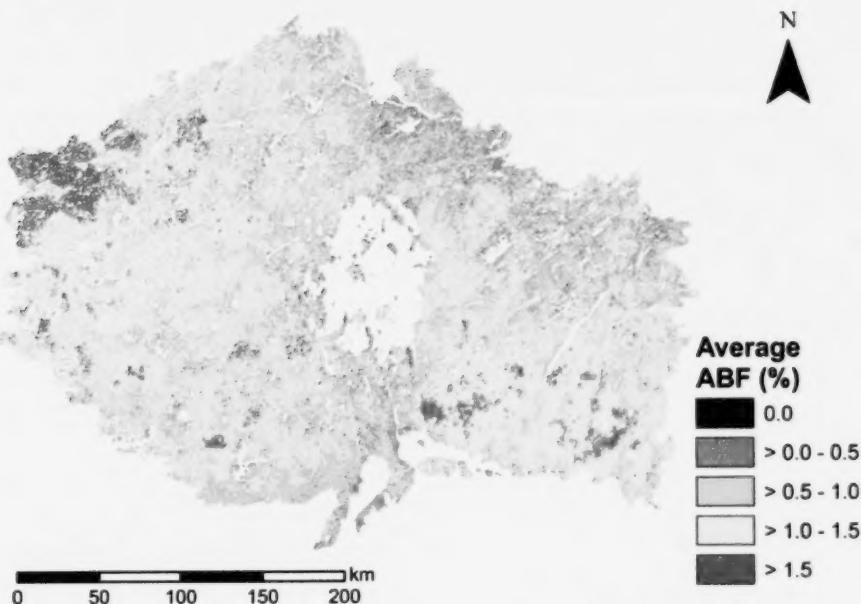

Figure 24. *Average annual burn fraction (%) in the case study area over 200 simulation years.*
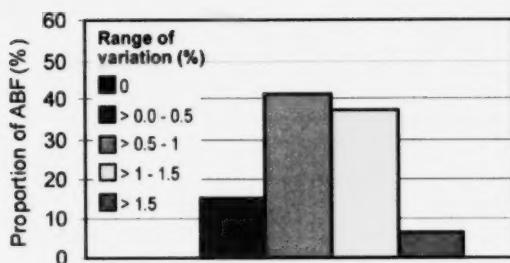
Figure 25. *Frequency distribution of the average annual burn fraction (%) in the case study area over 200 simulation years. Note: Proportions of categories sum to 100%.*
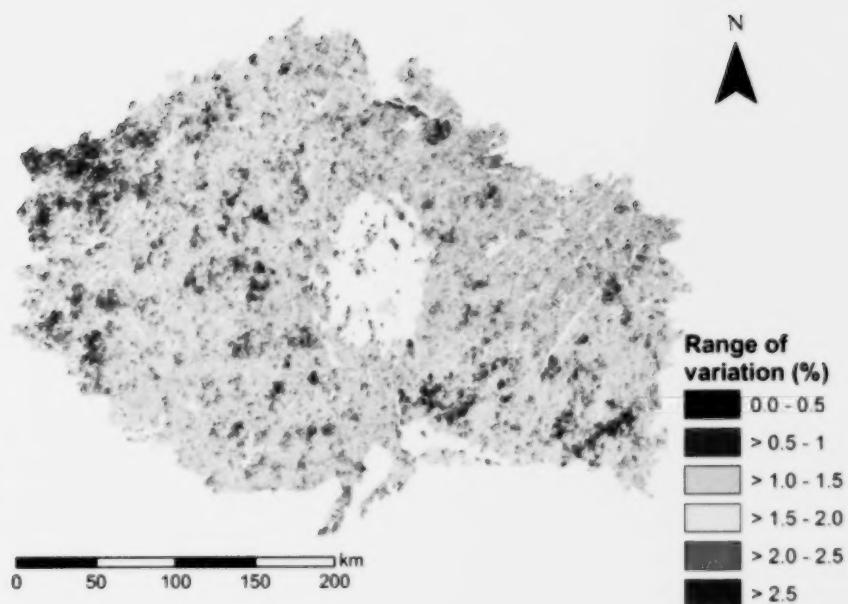
Figure 26. *The range of variation of average annual burn fraction (%) in the case study area over 200 simulation years.*
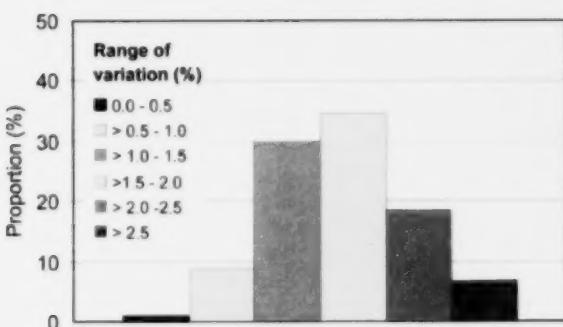

Figure 27. *Frequency distribution of the range of variation of the average annual burn fraction (%) in the case study area over 200 simulation years. Note: Proportions of categories sum to 100%.*

The conditional spatial FSD provides an indication of the average annual burn probability that, given a location burns it will be burned by fires of a particular size class. As illustrated in Figure 28, if a fire burns in the case study area, it is most likely to be between 1,000 and 10,000 ha or larger than 10,000 ha. Also areas near the edge of the case study area are most likely to be burned by fires that are between 1,000 and 10,000 ha, while those in the interior are most likely to be burned by fires larger than 10,000 ha. Figure 29 shows the frequency distribution of conditional burn probabilities.

The spatial FSD shows average annual burn probability or likelihood that a location will be burned by fires of a particular size class. Similar to the findings for conditional spatial FSD, the spatial FSD results indicate that fires in the case study area are most likely to be between 1,000 and 10,000 ha and larger than 10,000 ha. Also areas near the edge are most likely to be burned by fires between 1,000 and 10,000 ha while those in the interior are most likely to be burned by fires larger than 10,000 ha. Figure 30 shows the spatial FSD of the case study area and Figure 31 shows the frequency distribution of burn probabilities.
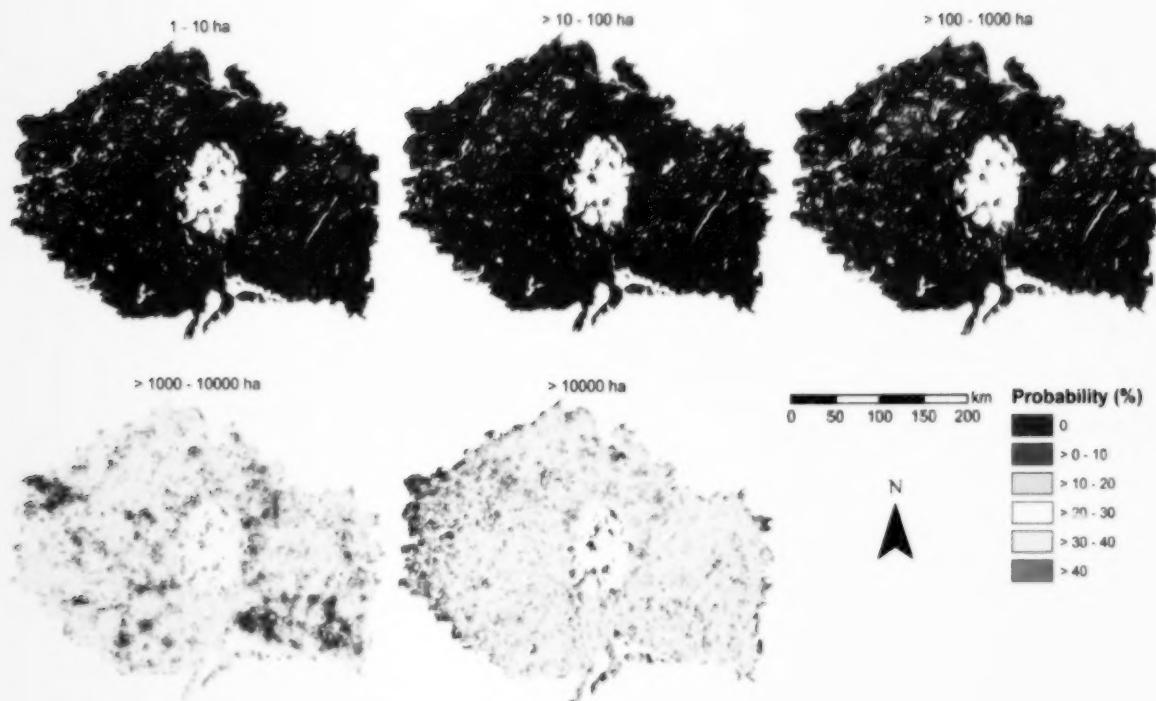
Figure 28. Conditional burn probability of a fire of a given size class, given that the location burns, in the case study area.
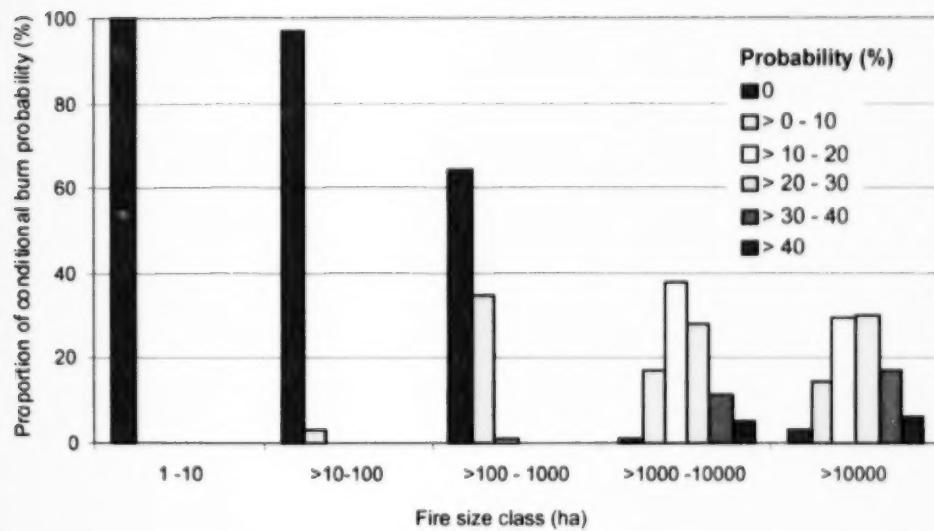
Figure 29. Frequency distributions of conditional burn probability for the case study area by fire size class given that the location burns. Note: Proportions of categories within size classes sum to 100%.
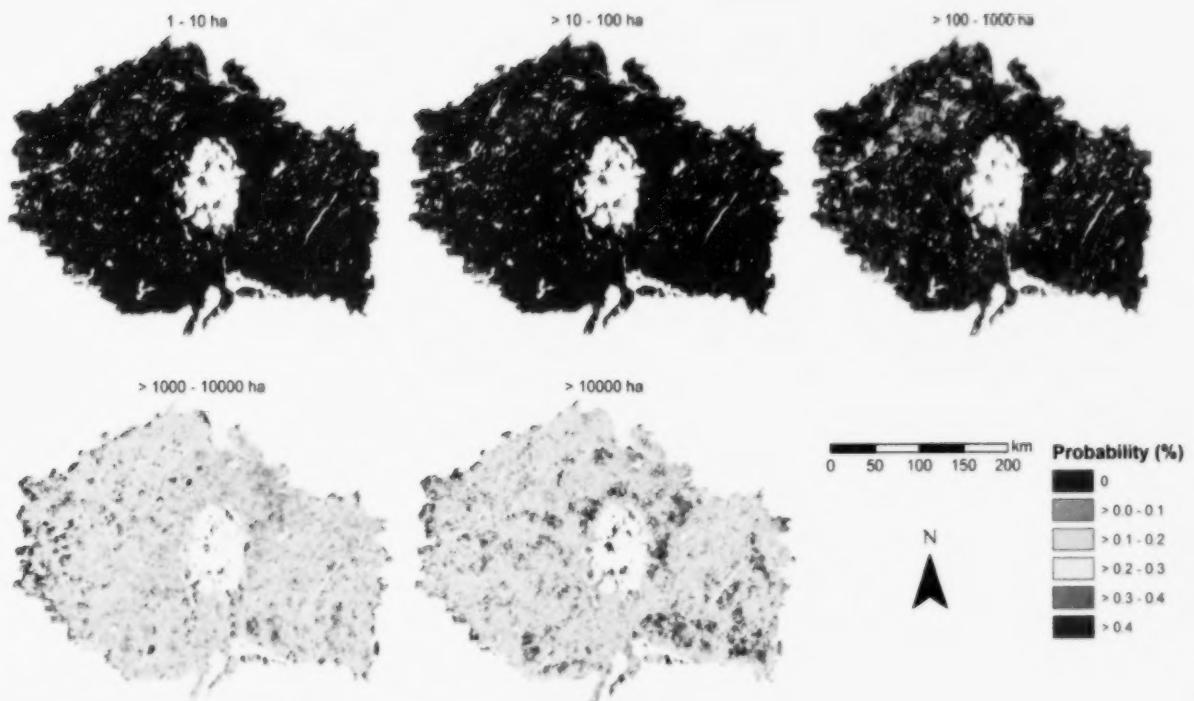
Figure 30. Burn probability of a fire of given size class in the case study area.
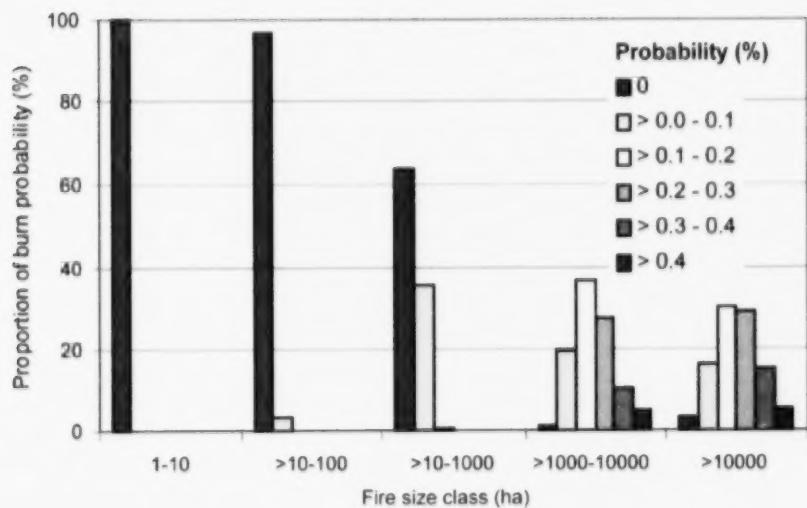

Figure 31. Frequency distributions of burn probability by fire size class. Note: Proportions of categories within size classes sum to 100%.

Spatio-temporal patterns of fire regime

Spatial burn probabilities

We analyzed the spatio-temporal pattern of the fire regime in the case study area over the 200-year period by examining spatial annual burn probability over a series of periods and annual burn probability for several specific simulation years. We also demonstrate how spatio-temporal trends of forest cover type and forest age can be studied using spatial probability of the presence of a particular forest cover type, of forest cover reaching a particular age, and of a particular forest cover type reaching a particular age.

Figure 32 shows the spatial annual burn probability of the case study area for 50-year periods of simulation years: 1-50, 51-100, 101-150, and 151-200. Spatial annual burn probability (value and pattern) varied over time though we did not quantitatively assess the differences. Figure 33 shows the frequency distribution of burn probabilities for the 50-year periods.

Figure 34 shows the spatial annual burn probability of the case study area for simulation years 1, 50, 100, 150, and 200. The spatial annual probability maps are "snapshots" of burn probabilities for the selected years, and also show variation in spatial annual burn probability over time. These snapshot probabilities stemmed from only 30 simulations, therefore spatial variation is high. Figure 35 shows the frequency distribution of spatial burn probabilities at simulation years 1, 50, 100, 150, and 200.
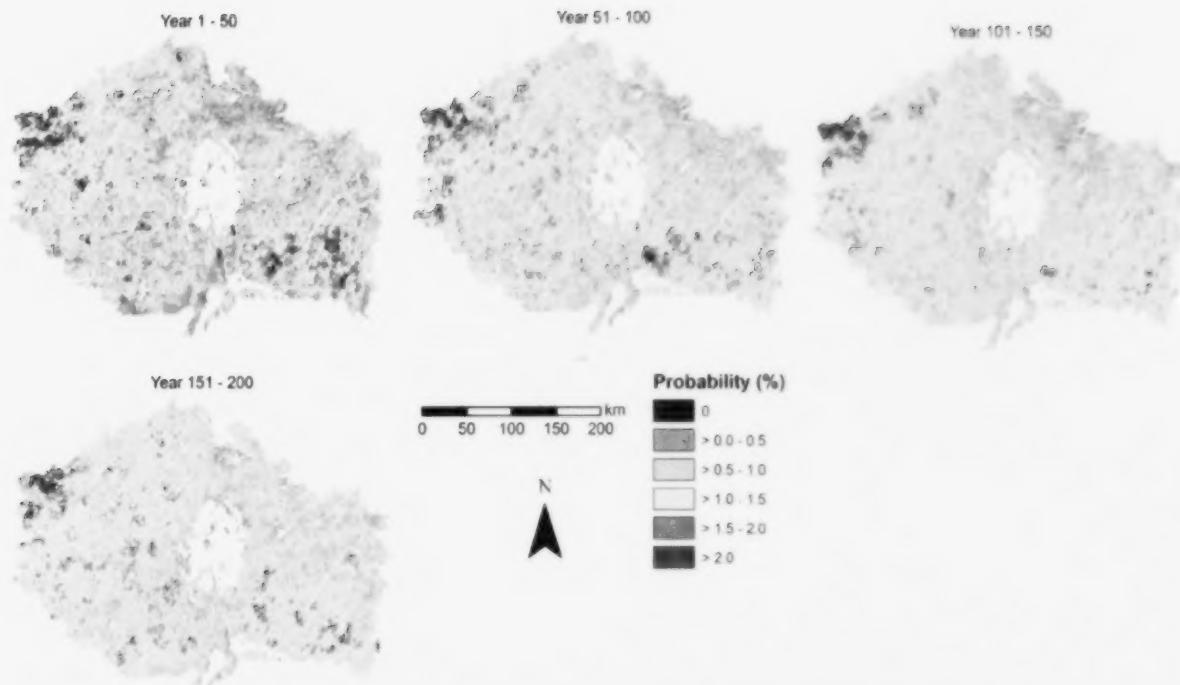
Figure 32. *Annual burn probabilities in the case study area for 50-year periods within the 200-year simulation period.*
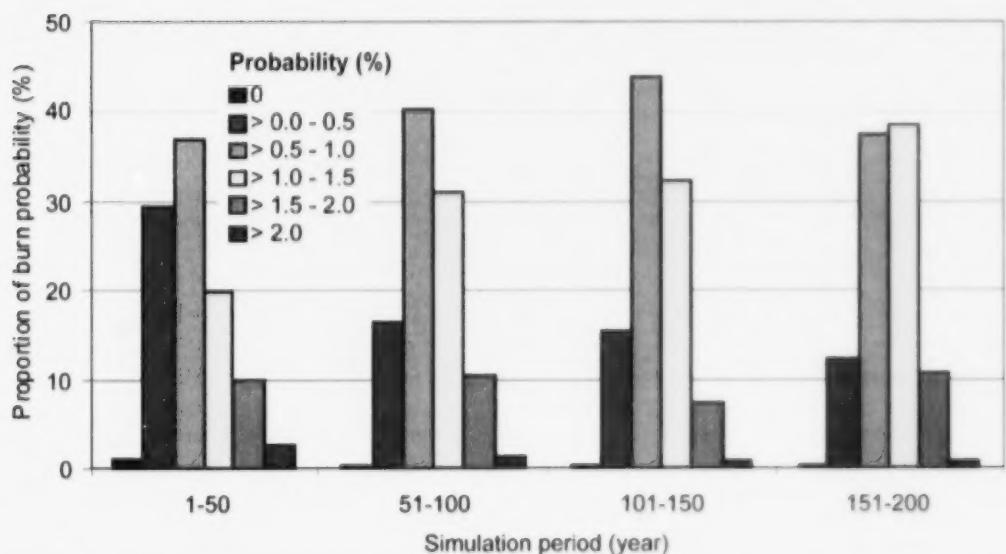
Figure 33. *Frequency distribution of annual burn probabilities in the case study area for 50-year periods. Note: Proportions of all burn probability categories sum to 100% for each simulation period.*
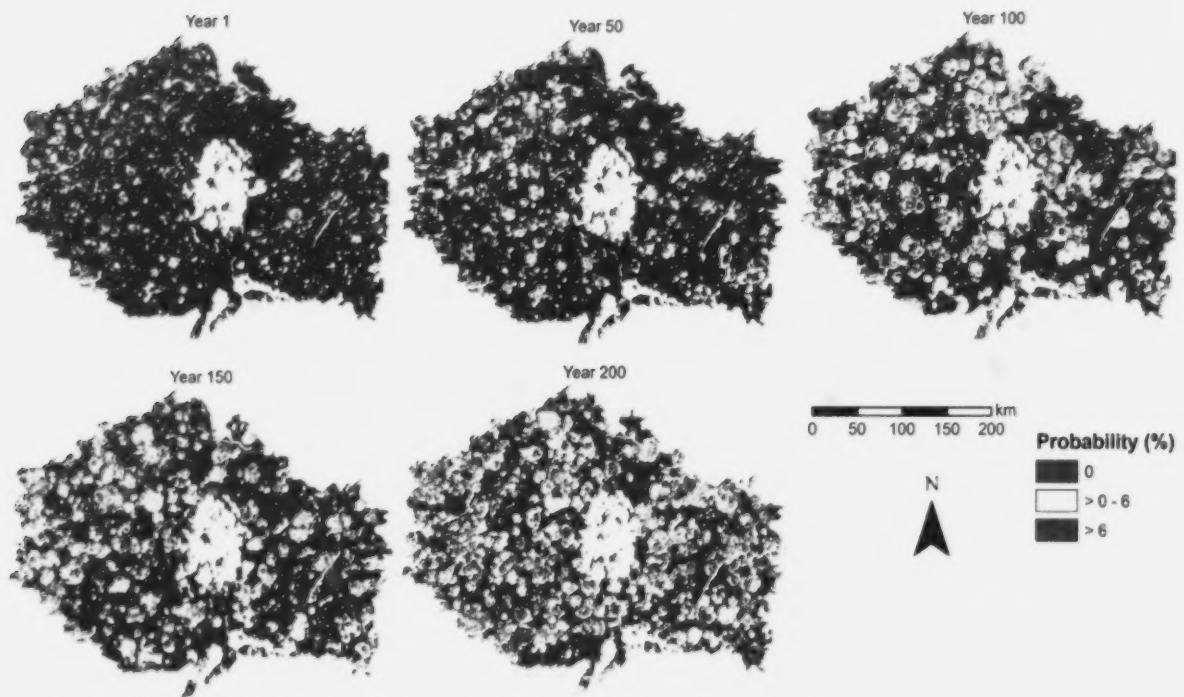
Figure 34. Burn probabilities in the case study area at simulation years 1, 50, 100, 150, and 200.
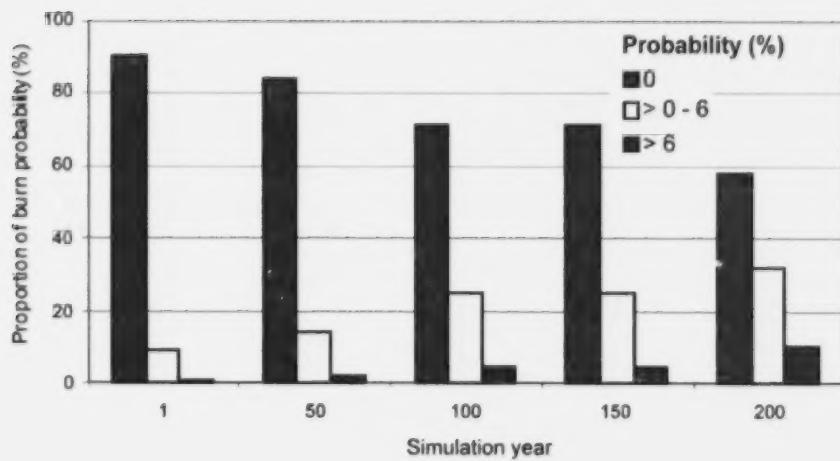
Figure 35. Frequency distribution of burn probabilities in the case study area at simulation years 1, 50, 100, 150, and 200. Note: Proportions of all burn probability categories sum to 100% for each simulation year.

Spatial and temporal probabilities of forest cover types and forest age

Figures 36 and 37 show and summarize the spatial and temporal probabilities of a particular forest cover type, SbDom (black spruce-dominated), occurring in the case study area. Both spatial pattern and overall probability varied over time. The spatial pattern was influenced by the eco-zone classification (Figure 6).
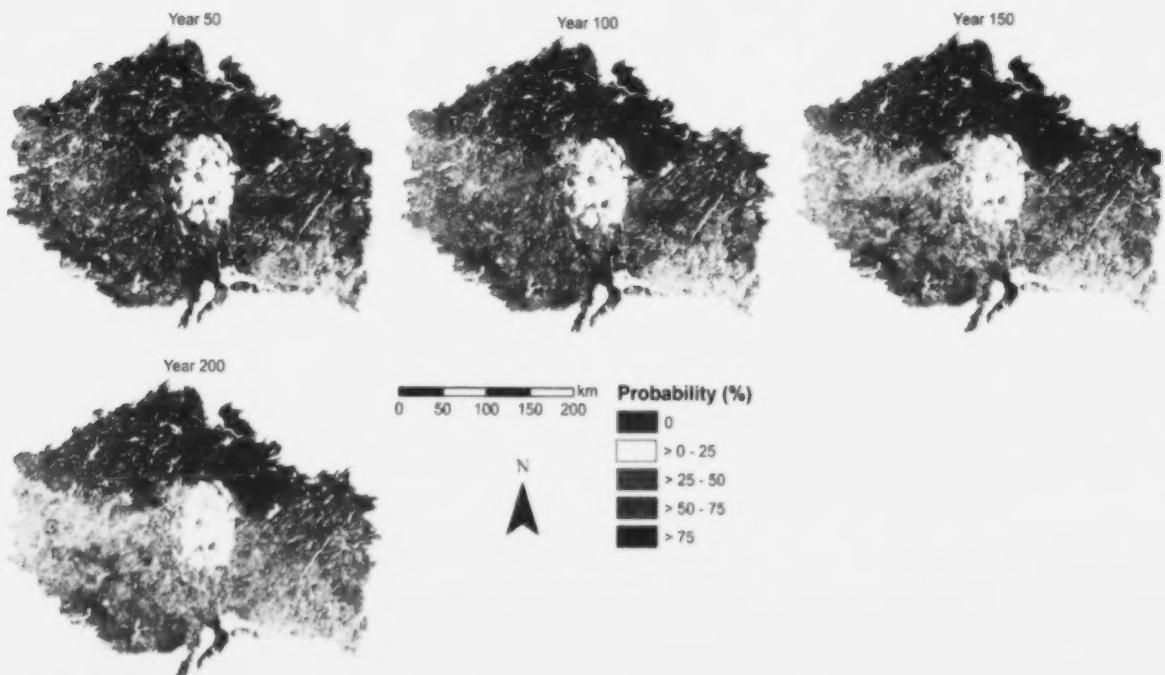
Figure 36. *Probability of the presence of forest cover type SbDom (black spruce-dominated) in the case study area at simulation year 50, 100, 150, and 200.*
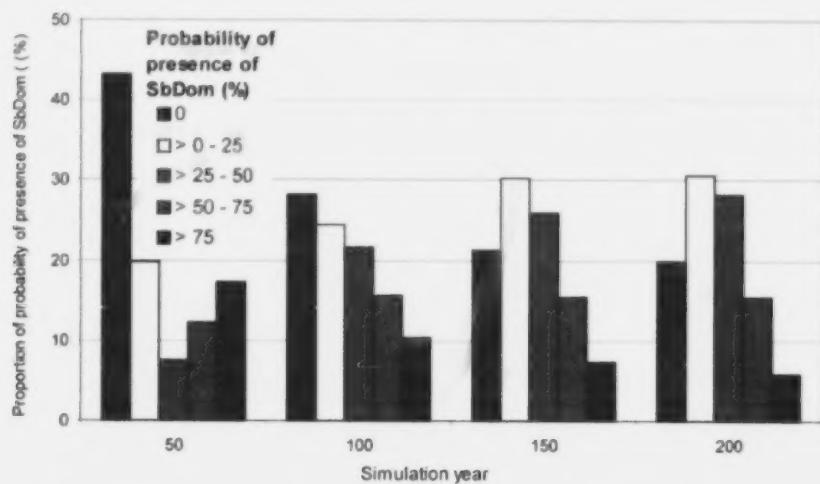
Figure 37. *Frequency distribution of probability of the presence of forest cover type SbDom (black spruce-dominated) in the case study area at simulation year 50, 100, 150, and 200. Note: Proportions of probability of presence of SbDom categories sum to 100% for each simulation year.*

Figures 38 and 39 show and summarize the spatial and temporal probabilities of the forest reaching a particular forest age, in this case 150, occurring in the case study area. Again, both spatial pattern and overall probability varied over time. The proportion of old forest (>180 years) increased with time.
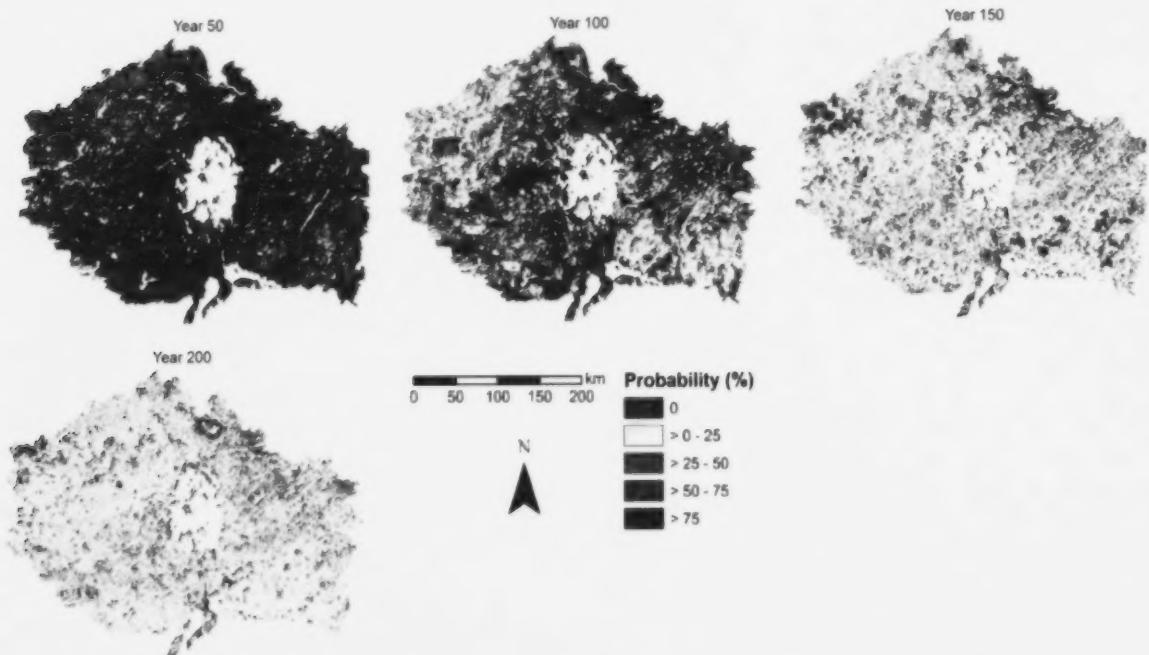
Figure 38. *Probability of forest cover types in the case study area reaching the age of 150 years or older at simulation year 50, 100, 150, and 200.*
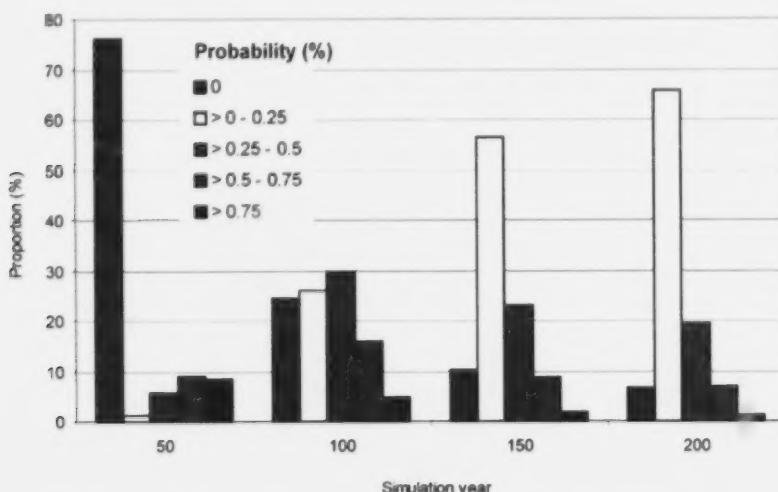
Figure 39. *Frequency distribution of probability of forest cover types in the case study area reaching the age of 150 years or older at simulation year 50, 100, 150, and 200. Note: Proportions of probability categories sum to 100% for each selected simulation year.*

Figures 40 and 41 show and summarize the spatial and temporal probabilities of a particular forest cover type, in this case SbDom, reaching a particular forest age, in this case 150, in the case study area. Both spatial pattern and overall probability varied over time.
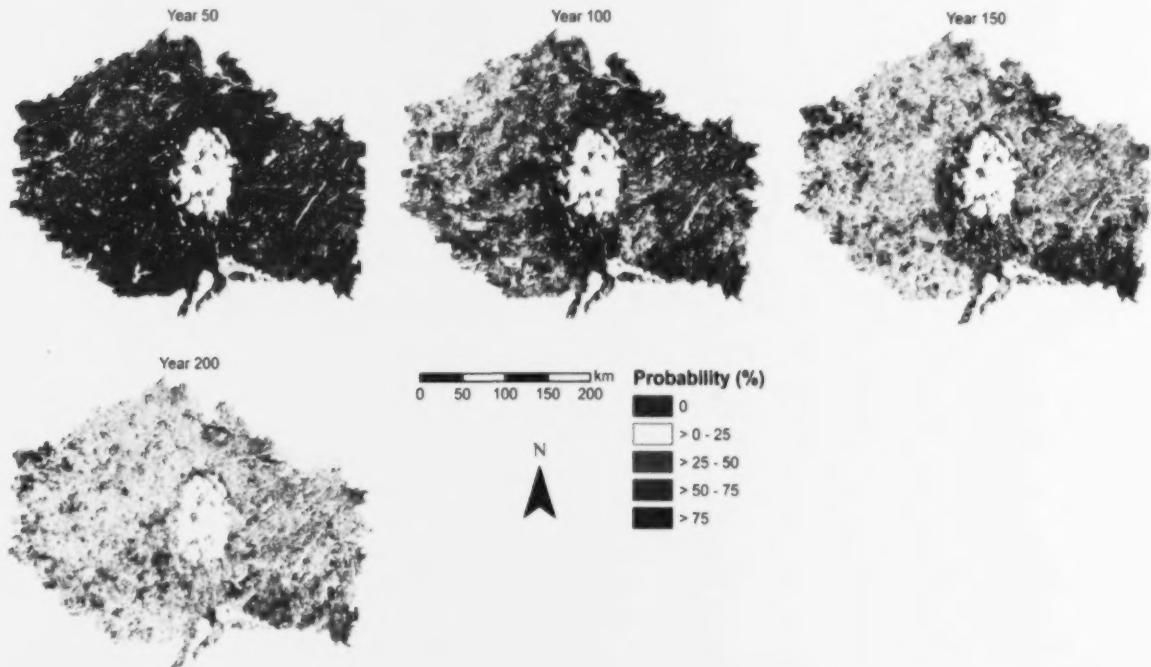
Figure 40. *Probability of forest cover type SbDom (black spruce-dominated) in the case study area reaching 150 years or older at simulation year 50, 100, 150, and 200.*
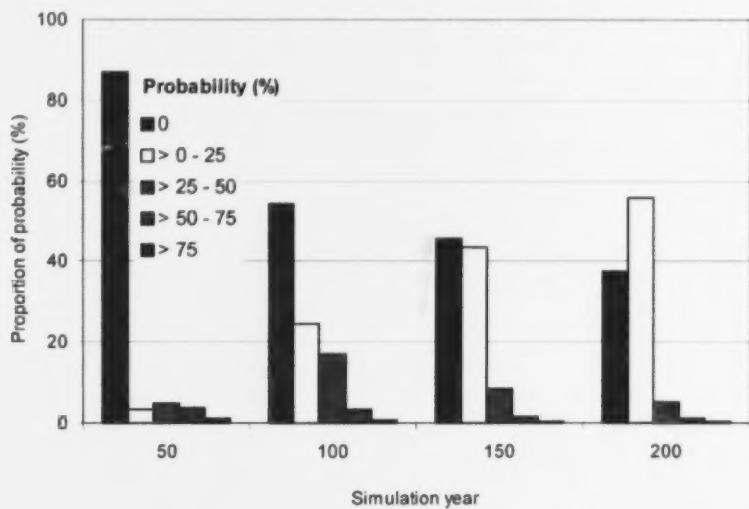

Figure 41. *Frequency distribution of probability of forest cover type SbDom (black spruce-dominated) in the case study area reaching 150 years or older at simulation year 50, 100, 150, and 200. Note: Proportions of probability categories sum to 100% for each simulation year.*

Discussion

We discuss both the simulated fire regime in the case study area and, more importantly, applications of BFOLDS in forest fire regime analysis. As indicated in previous sections, we emphasize how BFOLDS can be used in forest fire regime analysis rather than what the forest fire regime is in the case study area or why the simulated regime has specific ecological characteristic. Moreover, we have not demonstrated all possible forest fire regime indicators nor all aspects of those indicators. The indicators that we estimated, and their aspects, are listed in Table 5.

Table 5. Forest fire regime indicators and their aspects estimated in this case study (denoted by √).

Indicators	Aspect			
	Overall	Temporal	Spatial	Spatio-temporal
Annual burn fraction (ABF) (%)	√	√	√	
ABF by age class	√	√		
ABF by cover type	√	√		
Annual number of fires (ANF)	√	√		
Fire return interval (FRI)	√			
Fire size distribution (FSD)	√		√	
Age class		√		√
Forest cover		√		√
Burn probability (BP)				√

Characteristics of the fire regime

Overall forest fire regime

As an indicator of area burned, the average ABF over 200 years in the case study area was 0.97%. Similarly, as an indicator of number of fires, the average ANF was 49.4 per year and the average FRI was 105 years. However, for all these indicators, variability was high among the 30 simulations: average ABF varied from 0.83% to 1.55%, average ANF from 43.1 to 55.2, and average FRI from 64 to 121.

BFOLDS can be used to examine many forest fire regime indicators by age (class), forest cover type, forest fuel type, or other spatial properties used as inputs (see tables 2 and 3). As an example, we estimated average ABF by age class and forest cover type and found that, in general, in the case study area average ABF differs by age class. Particularly, the average ABF of the first age class (0, 20] was significantly lower than that for most other age classes because of the BFOLDS assumption that an area cannot re-burn within 10 years. We also found that average ABF varied widely within the same age class.

Similarly, average ABF differed by forest cover type. In general, the conifer and conifer-dominated mixedwood forest cover types had higher ABFs than the deciduous and lowland cover types. As was found for age, average ABF varied widely within the same forest cover types.

Fire size distributions can be illustrated and quantified in many ways. We selected two: using the cumulative density functions of fire sizes and classifying fires into six size classes: (0, 1], (1, 10], (10, 100], (100, 1,000], (1,000, 10,000], and (10,000, ∞]. Results show that the study area could be dominated by medium to large fires. However, variability was high for both cumulative density functions of fire sizes and within the same fire size classes among the 30 simulations. These results illustrate the variability in forest fire regime from the perspective of FSD.

From the simulated results of the overall fire regime indicators, it is evident that forest fire regime is a stochastic process and its indicators are highly variable.

Changes in fire regime over time

As discussed above, forest fire regime is a dynamic process that has spatial and temporal dimensions. As this case study shows, forest fire regime evolves over time.

Both the average ABFs and the average ANF of the 30 simulations over 200 simulation years show large variations by year. The general trend was that ABF increased and ANF decreased over time. This indicates that the average fire size increased over time. Variability of both indicators was high within years. These within-year variations were also significantly larger than that for overall ABF or ANF, respectively.

The temporal trend of forest cover and age class composition differed from one another, with considerable variation for each forest cover type or age class within years. The magnitude of variation in age class increased with time and eventually stabilized; younger age classes stabilized earlier than older age classes. As well, forest cover type variability differed among forest cover types.

From the simulated results of the temporal indicators, it is evident that forest fire regime evolves through time and with even higher variability within indicators than was found for the overall indicators.

Changes in fire regime over space

Annual burn fraction or ABP varied greatly over space as well as at each location. In general, the range of variation at a cell exceeded the absolute value of ABF.

The spatial and conditional spatial FSDs show that FSD varies over space. The case study area is most likely to be burned by fires that are between 1,000 and 10,000 ha and those larger than 10,000 ha. This supports the findings described above that indicated that the study area is dominated by medium to large fires. An interesting result is that areas near the edge of the case study area are most likely to be burned by fires between 1,000 and 10,000 ha while those in the interior are most likely to be burned by fires larger than 10,000 ha. This may be the result of an edge effect in the simulations resulting from fire area calculations. In this case study, for fires that spanned the buffer and the case study area, only the area within the case study area was included in fire size calculations (Figure 4). This might have changed the fire size classes from larger than 10,000 ha to between 1,000 and 10,000 ha.

Similarly, from the simulated results of the spatial indicators, it is evident that forest fire regime differs over space and with even higher variability within indicators than was found for the overall indicators.

Changes in fire regime over time and space

We examined forest fire regime both over time and space by estimating select spatial indicators over time, in this case a 50-year interval or period.

Spatial annual burn probability (both over a period and for a particular year) varied over time. To obtain more consistent values for annual burn probability for a particular year, more simulations (replications) are likely required as spatial variation for the snapshot probabilities from the 30 simulations was very high and the pattern seemed almost random. A reasonable estimate of burn probability might require thousands of simulations or iterations (Sànchez-Guisàndez et al. 2007).

Results of the case study also indicate that the spatial distribution and composition of forest age and forest cover type changed over time and space. These spatial patterns seemed to be influenced by the ecozone classification (e.g., Figure 36), indicating that local fire regime is affected by ecozone classification but is also controlled by forest succession rules.

Overall variability of forest fire regime

As discussed above, variability in forest fire regime was high as shown in the indicators overall, over space, over time, and over space and time. Also variability in indicators over space and time was higher than that for overall indicators resulting from aggregation. Much of the variability may result from randomness. If observed on a small spatial scale (for example, 10 ha) and over a short period (for example, one year) forest fires are relatively rare events though many fires might occur at landscape scale (for example, millions ha) over a long period (for example, centuries) (Cui and Perera 2008). As well, natural forest fire occurrence, spread, and extinguishment are stochastic over space and time, and that stochasticity is associated with combinations of climate/weather and spatial heterogeneity of forest landscapes in terms of topography and forest cover types (Heinselman 1973, Cui and Perera 2008, Perera and Cui 2009). Thirdly, previous fires affect subsequent fires both temporally and spatially. That is, fires might not occur in areas that recently burned or might stop spreading when they reach recently burned areas, as summarized by Cui and Perera (2008). All these factors complicate the stochasticity and thus contribute to the variability of forest fire regimes.

Using BFOLDS to simulate fire regimes

Fire regime simulation results from BFOLDS are not pre-determined; rather they are emergent properties of model logic, user assumptions, and input data. Also, because many elements of the model's logic and assumptions are stochastic, BFOLDS can be used to explore the probabilistic nature of fire regime characteristics. Therefore, BFOLDS is useful to address what-if questions about fire regime asked by researchers and land and resources managers. To date, BFOLDS has been used to examine spatial potential of old growth forest occurrence (Perera et al. 2003), spatial fire regime (Perera et al. 2004), effects of climate change on land use planning (Munoz-Marquez 2005), songbird habitat patterns under different forest policy scenarios (Rempel et al. 2007), effect of fire weather assumptions on fire size distributions (Perera and Cui 2009), and to evaluate policy guidelines of emulating natural disturbances patterns (Perera et al. 2009). BFOLDS has also been applied to characterize fire disturbance regimes to develop a new forest management guide for Ontario's boreal forest (http://www.mnr.gov.on.ca/en/Business/Forests/1ColumnSubPage/STEL02_164558.html). Beyond these, many other applications of BFOLDS are possible, ranging from investigations on patterns of fire severity, forest fuel consumption, carbon emission, residuals, and habitat supply.

At the same time, BFOLDS is only a simulation model and its results do not represent reality or forecasts of future fire regimes. Its output and simulation results are solely a construct of the model logic that attempts to represent the best scientific knowledge about fire processes and forest succession, and input data and user assumptions provided based on the user's best judgement. We remind the reader that, as with any scientific model, BFOLDS can be misused, either by using it invalidly (indefensible user assumptions and/or erratic input data) or misinterpreting its output. In addition, we emphasize that many knowledge gaps and uncertainties remain in the knowledge of forest fire processes and succession. Therefore, BFOLDS also represents these uncertainties, which are addressed by model and user assumptions in the interim, as illustrated in Figure 42. As the knowledge becomes more certain and better databases are developed, BFOLDS will evolve to accommodate these improvements.
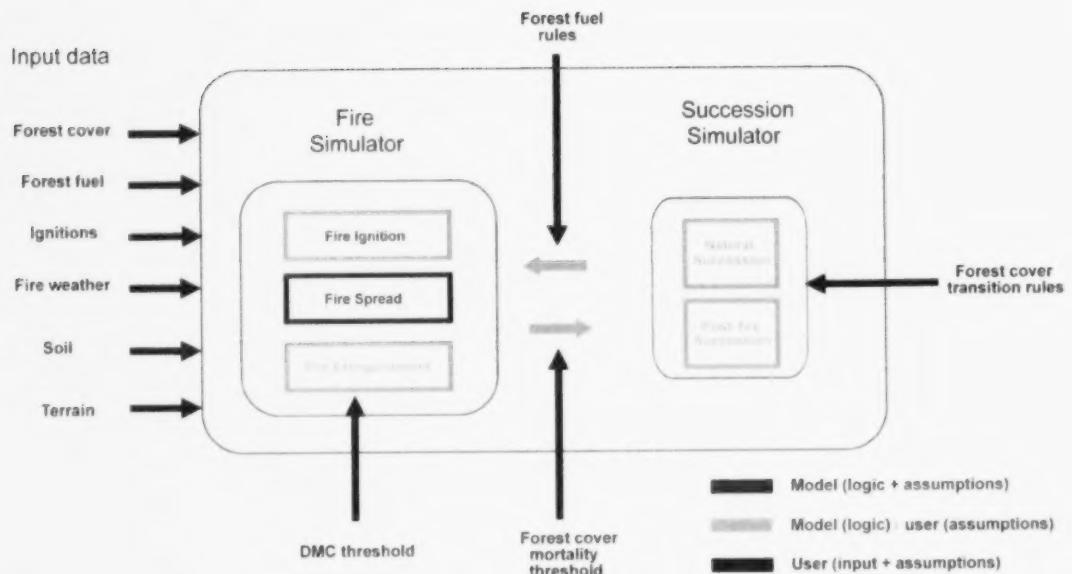
Figure 42. Schematic depiction of the model assumptions and user assumptions that affect different components of BFOLDS (from Perera et al. 2008).

In summary, BFOLDS offers a scientifically sound and logically intuitive method to investigate boreal forest fire regimes that are highly complex. When used judiciously, with proper data and assumptions, it is a useful tool to quantify many characteristics of fire regimes and to explore their spatial, temporal, and stochastic variability, which is difficult or impossible to accomplish using empirical approaches.

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